Founded 1925
Incorporated by Royal Charter 1961
To promote the advancement of radio, electronics and kindred subjects by the exchange of information in these branches of engineering

Volume 51 No. 4 April 1981

The Radio and Electronic Engineer

The Journal of the Institution of Electronic and Radio Engineers

Radio and Radar Ignition Hazards

FOR about three decades, it has been thought that ignition risks might exist at plants processing flammable gases and vapours if the metal structures of the plants were to act as aerials and deliver radio frequency energy into electric sparks. Studies of this possibility involve consideration of several disparate and teasing engineering problems. As a further complication it is probably true to say that it is more difficult to ignite releases of flammable gases or vapours on an open air plant than it is to ignite controlled gas concentrations under laboratory test conditions.

First of all, an assessment is necessary of the likely efficacy of the plant structures as aerials. These structures are generally randomly orientated and contain complex arrangements of pipes, vessels and supporting steel work which do not resemble simple aerial configurations. Then the behaviour of these improbable aerials is also affected by the transient nature of the load—typically an intermittent spark of widely varying impedance during the arc discharge. Further complexities are introduced if more than one radio or radar transmission is involved and due account needs to be taken of possible field enhancements.

Not least among the problems is that of discovering appropriate gas ignition thresholds. Threshold ignition values for various gases and vapours have been thoroughly researched for d.c. and power frequency electric arcs but the ignition of gas from a radio-frequency source raises new problems, particularly when the source impedance presented to an intermittent spark may vary considerably for different structures.

These fascinating problems were comprehensively tackled in 1978–1979 by a group of engineers drawn from widely different organizations. The organizations concerned were the Ministry of Defence, Total Oil Marine, Shell UK Exploration and Production, the British Gas Corporation, and the Health and Safety Executive. They were supported by staff of ERA Technology and the University of Bradford. The group faced a difficult and pressing radio-frequency ignition problem at St Fergus in Scotland where a large Ministry of Defence radio station was constructed near to a major industrial complex consisting of a gas terminal and two processing plants. Work on radar ignition problems was jointly undertaken by some of these organizations in connection with proposals for new developments on the Firth of Forth.

The urgency under which these projects were undertaken was met by the participating organizations with considerable determination and mutual co-operation. Throughout the exercise, which lasted about 18 months, there was a constant interchange of ideas and a pooling of technical resources. The group was able to base its work on earlier research to which the University of Bradford had been a notable contributor. Unlike the pioneer workers, however, the group had access to working processing plants and, under strict safety provisions, were able to make direct measurements of induced currents and voltages in plant structures for known radio transmissions. Their work has resulted in new understandings of these difficult problems and the results of their investigations have been made available to the British Standards Institution for use in a new applications guide.

Whether radio or radar frequency sparks might be hazardous depends greatly on whether escapes or releases of flammable gases or vapours might occur. Modern plants are so designed and constructed as to minimize both the likelihood and extent of escapes so that ignition risks generally are reduced to very low levels. But that is another story.

ALLEN HALL

Mr A. Hall, B.Sc., C.Eng., F.I.E.E., is Deputy Chief Inspector of Factories with the Health & Safety Executive; he was chairman of the Steering Committee on radio frequency hazards at St Fergus.

Members' Appointments

CORPORATE MEMBERS

P. Denby (Fellow 1976, Member 1958, Graduate 1952) has taken an early retirement from the BBC where for the past six years he has been manager of the Studio Group in the Designs Department. During this period he has been particularly concerned with the development of the BBC digital standards convertor and of videotape editing equipment. Mr Denby first joined the BBC in 1941 and after four years service in the Royal Air Force he returned to the Corporation in 1947 as a maintenance engineer. He was a member of the Institution's Paper Committee from 1976 to 1980.

T. B. McCrirrick (Fellow 1962, Member 1954, Graduate 1953), Director of Engineering of the BBC since 1978, has accepted an invitation to become President of the Society of Electronic & Radio Technicians, effective from 1st January 1981. He succeeds Air Vice Marshal A. A. Morris, who had held the office for five years. Mr McCrirrick joined the Corporation in 1943, and has held a succession of posts, mainly since 1949 on the studio engineering side of television. From 1970 to 1971 he was Chief Engineer (Radio Broadcasting) and then assistant director of engineering; in 1976 he became deputy director of engineering. He served on the Institution's Papers Committee from 1973 to 1976.

I. W. Peck (Fellow 1966, Member 1959) has transferred within the Plessey Group and is now a Senior Project Manager at Plessey Radar, Cowes. Prior to retiring from the army in 1973, he held a number of appointments at government establishments and headquarters concerned with procurement of guided missiles and electronics, lastly as Assistant Director of Guided Weapons in the Ministry of Defence Procurement Executive, with the rank of Colonel.

G. P. Thwaites, B.Sc. (Eng) (Fellow 1955, Member 1944) has joined Zaerix Electronics as a consultant. The company has recently acquired from Thorn Brimar the Mazda radio valves and tubes marketing and distribution business based in Rochester. Mr Thwaites has been associated with Thorn Brimar and its predecessors (the Foots Cray valve factory of Standard Telephone and Cables) since 1934 and up to his retirement earlier this year had been general director of the Rochester operation since 1971. Mr Thwaites was for several years a member of the Programme and Papers Committee. He also assisted the Education Committee in connection with the specialist subject of the Graduateship Examination on Valve Manufacture and Technology.

N. Wheatley (Fellow 1973, Member 1970, Associate 1961), General Manager of the Bahrain International Communications Division of Cable & Wireless since 1978 has returned to the UK and is now with the Engineering Inspectorate section of the Engineering Department at the company's London headquarters. Mr Wheatley was previously manager of International Relations with Cable & Wireless in Hong Kong and during his tour of duty he took a leading part in the formation of the Hong Kong section of the Institution and was its first chairman. In 1970 he contributed a paper to the Journal discussing the planning and commissioning of the communications satellite earth station at Bahrain.

D. B. Butler, M.Sc. (Member 1973) who joined the New South Wales Department of Technical Education in 1973 following service in the Royal Navy as Instructor Lieutenant Commander, is now a lecturer in the Department of Marine and Electrical Engineering at the Australian Maritime College, Launceston, Tasmania.

D. C. Callender (Member 1959, Graduate 1953) who has been with the BBC for 39 years has recently retired. For the past 13 years he was head of the Sound Section in the Studio Capital Projects department.

Sqn Ldr B. B. Canton, RAF (Ret.) (Member 1973) has completed four years with the air defence environment team at the Ministry of Defence and has now retired from the service.

Y. K. Chu, M.Sc. (Member 1980, Graduate 1974), formerly a senior development engineer with Philips Croydon, has been appointed a member of the scientific staff at Bell Northern Research, Ottawa.

E. D. Dobson (Member 1967) has been appointed head of long range strategic planning section in the technology executive of headquarters of British Telecommunications. Mr Dobson has been with the Post Office since 1945 apart from two years' break for national service in the Royal Signals.

M. K. Dutta, B.Sc. (Member 1973, Graduate 1970) is now an associate engineer with Mobil Research and Development Corporation, Princeton, New Jersey. After working in India with the Gujarat State Fertilizers Company as planning engineer, he went to the USA in 1975 and joined the Hoechst Corporation in Massachusetts.

Flt. Lt. P. M. Eckert, B.Sc. (Member 1976, Graduate 1972) is taking the Engineering Air Systems Course at the RAF College, Cranwell, following two years as Officer Commanding Systems Flight, RAF Leuchars, Scotland.

J. A. Ferla, M.Sc. (Member 1973, Graduate 1961) has completed a year's appointment as professional tutor in education at the Hastings College of Further Education and is now senior lecturer in charge of electrical engineering at Malawi Polytechnic.

H. C. J. M. Gilpin (Member 1973, Graduate 1966) has recovered from the illness which caused his retirement from service with the Ministry of Defence in Sierra Leone and is now working as a consulting engineer in Freetown, Sierra Leone.

A. Marshall, B.Sc. (Member 1977), formerly Systems/Trials Engineer with EMI Electronics, Feltham, has been appointed Avionics Systems Engineer with the British Aerospace Aircraft Group at Kingston.

NON-CORPORATE MEMBERS

E. O. Awala (Graduate 1969) has been appointed Principal of the Posts & Telecommunications training centre at Kano, Nigeria. He has been with the Nigerian Posts and Telecommunications department since 1972 and prior to taking up his present position was a principal engineer at Posts & Telecommunications headquarters in Lagos.

M. G. Rapps (Graduate 1971) who has been with Beckman Instruments as sales engineer for the past five years, is now sales manager (components) with the company.

W. Wallace (Graduate 1968) has joined the Metal Box Company's research and development division at Wantage, Oxfordshire, as development engineer. For the past 10 years he has been a technical officer at the Rutherford Laboratories of the Science Research Council at Culham.

R. Winstanley (Graduate 1971) who has been working with Deckel UK, Leeds, as development engineer has moved to the German based company Deckel Erodier Technik as senior development engineer—E.D.M. machine tools.

Capt. G. W. Blackburn, B.A., R.N. (Associate Member 1978) who is senior lecturer in radar at the City of London Polytechnic, has formed Blackburn Maritime Consultants to provide consultancy services on marine radio, radar and other electronic navigational aids.

Lt Cdr P. W. Hammond, RN (Associate 1978) who formerly held an appointment on the staff of the Captain Weapons Trials, has been appointed Weapons Engineer Officer, Submarine Tactics and Weapons Group of the Third Submarine Squadron.

Sgt I. F. V. Newcombe (Associate 1979), who was with the 25th Squadron RAF, Wildenrath, has been appointed technical supervisor on a *Bloodhound* missile section.

Letters to the Editor

From: **R. A. Nair,** M.E., Ph.D.
R. Hazelett
Prof. R. A. Waldron, M.A.., Sc.D, C. Eng F.I.E.R.E.

Comments on 'A high-gain multimode dielectric-coated rectangular horn antenna'*

There is nothing substantial in Dr Kumar's comments,† and the inferences published in our paper* are absolutely correct and valid.

The radiation patterns given in Figs. 2 (a), 2 (b) and 5 (a) are for the angles between 0 and 90 degrees, and the patterns are symmetrical about the horn axis giving an approximately mirror image of the shown patterns on the left-hand side as illustrated in Fig. A.

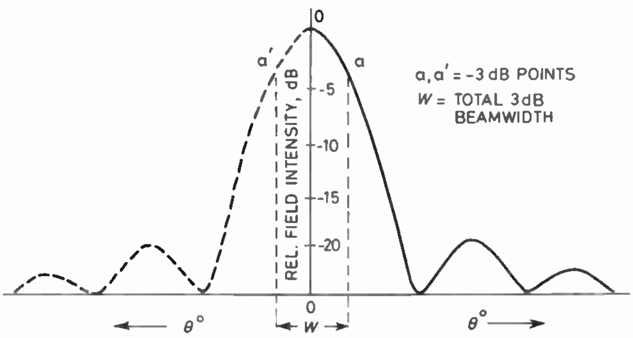


Fig. A.

Hence the actual 3dB beamwidth of the antenna is exactly twice of what can be read from patterns of Figs. 2 (a), 2 (b) and 5 (a). This representation in fact conforms to the practice adopted in most Journals.

However, there is a slight discrepancy ($\sim 0{\cdot}5^\circ$) in the result for 11·4 GHz and this is due to the deliberate attempt in making the two curves (which are very closely spaced, particularly up to $\sim 20^\circ$) in Fig. 5 (a) for frequencies 9·64 GHz and 11·40 GHz distinct without overlapping.

Table 1. Comparison of results from Figs. 2 (a), 2 (b), 5 (a) and 5 (b) of the paper

Frequency GHz	Half 3dB beamwidth degrees	Total beamwidth of the antenna depicted in Fig. 5 (b) degrees
8·36	~ 19·75 (from Fig. 5 (a))	~ 39·5
9·64	~ 19·00 (from Figs. 2 (a), 2 (b) and 5 (a)	~ 38·0
11·40	~ 18·0 (from Fig. 5 (a))	~ 36·5

R. A. Nair

Department of Electrical Engineering
College of Engineering
University of Mosul
Iraq

5th January 1981

*Nair, R. A., Kamal, A. K. and Gupta, S. C. 'A high-gain multimode dielectric-coated rectangular horn antenna', *The Radio and Electronic Engineer*, **48**, pp. 439–43, September 1978.

†Kumar, A., *The Radio and Electronic Engineer*, **50**, 536, November/December 1980

The Einstein Myth and the Ives Papers

Professor R. A. Waldron obviously tried to do justice to the book we edited, 'The Einstein Myth and the Ives Papers'*. Yet he made the common error of confounding mathematical form with physical content.

Certain of the mathematical expressions of Ives' theory are identical to those which express the Special Theory of Relativity. Yet the theories are entirely different in that the symbols have different meanings. Indeed, in the STR, some symbols are each accorded a continuum of mutually incompatible physical meanings, as though physical interpretation did not matter.

It is this incoherence which Ives corrected, through his extending and sharpening the Lorentz 'ether' theory, a theory which has never been disproven. Our book is Ives first and last. The other reprinted material in it was either found through Ives' footnotes or was selected according to what Dr. Turner and I thought Ives would have wished. Professor Waldron claims that the book 'cannot be regarded as a significant contribution to the development of physics.' But to have resolved contradictions in the most highly touted theory in science, to have achieved coherence in the understanding of such fundamental concepts as space and time, is surely a significant contribution. If it is not, then what is? Ives went on to perform a similar feat with respect to the General Theory of Relativity.

Most of the human race, when they think at all, think physically and not mathematically. Most mathematicians and even theoretical physicists think mathematically and not physically. Ives did justice to both modes of thought. This being so, Ives is a man from whom one can learn much *physics*, the discipline of which mathematics is the handmaiden that alone enabled it to rise and flourish.

Waldron correctly notes that electrodynamics was omitted from the book. From correspondence, we know that Ives planned to tackle the paradoxes in electrodynamics, but his demise intervened, as alluded to on p. xxiii.

Richard Hazelett

451 West 200 South
Provo
Utah 84601
USA

24th November 1980

I agree with Mr Hazelett that 'to have resolved contradictions in [Einstein's special theory of relativity], to have achieved coherence in the understanding of such fundamental concepts as space and time' would certainly be 'a significant contribution', if it had been done, but Ives did not do that.

The business of physics is to formulate theories which account for the primary facts of direct observation—tracks in cloud chambers, pulses in scintillation counters, positions of pointers on dials. Theories are written in mathematical language, which has no objective meaning except at its points of contact with the real world—the above primary facts.

The Radio and Electronic Engineer*, **50, no. 8, p.396, August 1980.

Therefore a theory consists in its mathematical structure. If two writers use the same mathematics, they are using the same theory; their subjective opinions about metaphysical interpretations of the mathematical structure—as distinct from the primary facts and their mathematical representation—are irrelevant. In accordance with this view, I have argued elsewhere† that Einstein's special theory of relativity is nothing but a modified formulation of the Lorentz theory of electrons. Both theories amount in essence to the Lorentz transformations; the rest follows automatically. That Lorentz argues from the aether while Einstein explicitly denies the existence of the aether does not mean that their theories were different; I have argued that Einstein was mistaken in denying the aether and that it is implicit in his theory. Ives also uses the aether, and as Mr. Hazelett says, his mathematical structure is the same as Einstein's and therefore the same as Lorentz's. Which is to say that it is the same theory, with a minor difference in the manner of presentation.

R. A. Waldron

School of Mathematics
Ulster Polytechnic
Newtonabbey, Co. Antrim, BT3 0QB
11th December 1980

†Waldron, R. A. 'The Wave and Ballistic Theories of Light—a Critical Review' (Frederick Muller, London 1977).

Standard Frequency and Time Service

Communication from the National Physical Laboratory

Relative Phase Readings in Microseconds NPL—Station

(Readings at 1500 UTC)

NOVEMBER 1980	MSF 60 kHz	GBR 16 kHz	Droitwich 200 kHz	DECEMBER 1980	MSF 60 kHz	GBR 16 kHz	Droitwich 200 kHz	JANUARY 1981	MSF 60 kHz	GBR 16 kHz	Droitwich 200 kHz
1	1·3	13·6	27·0	**1**	1·3	13·1	23·4	**1**	1·9	13·2	13·2
2	1·3	13·4	27·0	**2**	1·1	12·6	23·2	**2**	1·8	11·6	12·8
3	1·3	14·6	26·9	**3**	1·3	13·1	23·0	**3**	2·0	12·7	12·4
4	1·3	13·1	26·8	**4**	1·3	14·6	22·7	**4**	1·9	12·7	11·8
5	1·4	11·6	26·9	**5**	1·3	13·1	22·5	**5**	1·8	12·2	11·4
6	1·1	11·6	26·8	**6**	1·5	14·3	22·1	**6**	1·9	11·6	11·1
7	1·1	11·6	26·8	**7**	1·3	14·9	21·8	**7**	2·2	13·3	10·7
8	1·1	13·1	26·8	**8**	1·1	•	21·5	**8**	1·8	11·3	10·3
9	1·1	13·8	26·7	**9**	1·3	15·1	21·2	**9**	2·0	12·3	9·9
10	1·1	13·8	26·6	**10**	1·3	12·8	20·9	**10**	1·8	12·6	9·4
11	0·9	12·6	26·6	**11**	1·3	12·7	20·8	**11**	2·0	13·3	9·0
12	1·1	12·9	26·7	**12**	1·5	12·9	20·5	**12**	2·0	10·8	8·6
13	0·9	13·4	26·6	**13**	1·5	13·2	20·2	**11**	2·1	12·7	8·2
14	0·9	13·5	26·6	**14**	1·3	12·5	19·7	**14**	1·9	12·4	8·0
15	0·7	12·1	26·9	**15**	1·5	12·1	19·3	**15**	1·9	13·5	7·7
16	0·9	12·1	26·9	**16**	1·5	10·8	18·8	**16**	2·1	12·6	7·2
17	0·9	12·6	26·8	**17**	1·3	12·8	18·6	**17**	2·1	13·9	6·8
18	1·2	11·6	26·7	**18**	1·5	11·8	18·3	**18**	2·1	12·0	6·4
19	1·0	13·6	26·7	**19**	1·5	11·7	18·0	**19**	2·0	12·3	5·9
20	1·0	14·3	26·6	**20**	1·5	12·1	17·8	**20**	2·0	12·8	5·5
21	1·2	13·4	26·5	**21**	1·5	12·0	17·4	**21**	2·0	12·8	5·0
22	1·0	12·6	26·0	**22**	1·6	12·4	17·1	**22**	2·0	11·5	4·6
23	0·8	14·8	25·5	**23**	1·7	12·8	16·8	**23**	2·0	11·4	4·1
24	1·1	13·6	25·0	**24**	1·7	12·4	16·3	**24**	2·0	10·8	3·4
25	1.1	•	24·7	**25**	1·9	12·3	16·0	**25**	2·1	11·4	2·7
26	1·1	13·6	24·4	**26**	1·9	10·8	15·5	**26**	2·2	12·0	2·2
27	1·1	13·6	24·2	**27**	1·9	12·1	14·9	**27**	2·1	13·8	2·8
28	1·1	13·6	24·0	**28**	1·8	12·5	14·6	**28**	2·3	13·4	3·5
29	1·3	12·6	23·8	**29**	1·9	10·3	14·3	**29**	2·3	12·1	4·1
30	1·3	13·1	23·5	**30**	1·9	10·8	13·9	**30**	2·3	12·3	4·7
				31	1·9	12·2	13·6	**31**	2·4	12·4	5·3

Notes: (a) Relative to UTC scale (UTC_{NPL}–Station) = +10 at 1500 UT, 1st January 1977.
(b) The convention followed is that a decrease in phase reading represents an increase in frequency.
(c) 1 μs represents a frequency change of 1 part in 10^{11} per day.

UDC 621.3–768.3: 621.3.029.53
Indexing Terms: Spark discharges, r.f., Gases, ignition, R.f. hazards
Electromagnetic compatibility

Radio frequency ignition hazards

D. J. BURSTOW, B.Sc.*, R. J. LOVELAND, Ph.D.*, R. TOMLINSON,†
and
D. W. WIDGINTON, B.Sc.†

SUMMARY

In 1978, extensive investigations, co-ordinated by the Health and Safety Executive, were performed in order to evaluate possible radio frequency ignition hazards arising from the existence of radio transmitters in the vicinity of plants containing flammable liquids and gases. This paper, which is in three parts, describes the research work carried out by the HSE in order to assess the incendivity of r.f. discharges from loop-type structures acting as adventitious receiving aerials at frequencies up to 10 MHz and from dipole type structures at frequencies up to 9 GHz. In addition an assessment is given of the effect of multiple transmissions on ignition threshold power extractable from structures acting as adventitious receiving aerials.

1 Introduction

In order to assess the risk associated with radio transmissions from the Royal Naval (RN) transmitting station at Crimond, Scotland, to the North Sea gas processing plants at St Fergus, some 5 km from RN Crimond, the Health and Safety Executive (HSE) co-ordinated an extensive programme of tests and research during 1978.[1,2] The basic aim of the investigation was to determine the levels of field strength at which incendive sparks might occur when structures containing potential discontinuities were irradiated.

In the course of the investigations, extensive measurements of induced voltage and available power were made by ERA on actual structures in order to assess the electrical characteristics of such structures acting as adventitious receiving aerials. In conjunction with these on-site tests an extensive programme of research into the incendivity of radio frequency discharges was carried out by the University of Bradford, Shell Research and the HSE.

This paper reports on the research work carried out by the HSE and is split into three parts. The first part describes work carried out by the Research and Laboratory Services Division (RLSD) to assess the incendivity of r.f. discharges from various sources at frequencies up to 10 MHz; the second part describes the field work which was carried out to assess the incendivity of r.f. discharges from dipoles irradiated by pulsed radar transmissions; the third part describes an assessment of the power available from an adventitious receiving aerial when irradiated at the same time by more than one frequency.

Part 1 IGNITION OF FLAMMABLE GASES BY RADIO FREQUENCY DISCHARGES FROM TUNED LOOPS AND 50 Ω RESISTIVE SOURCES IN THE FREQUENCY RANGE UP TO 10 MHz

D. W. Widginton

This part deals mainly with how electrical discharges can be produced in 50 Ω circuits and in equivalent circuits representing loop structures and how the incendivity of such discharges caused by radio transmissions of up to 10 MHz in frequency can be characterized.

Previous work on spark ignition at radio frequencies[3–7] deals almost exclusively with reputedly purely resistive sources. The draft revision of BS 4992[3] considered that tuned loops would represent the worst-case receiving structure for frequencies up to about 30 MHz, and made the assumption that the incendive properties of discharges from such tuned loops could be inferred directly from the ignition threshold information available for 50 Ω resistive circuits.

* *Electrical Consultant Section of HM Factory Inspectorate, HSE Chapel Street, London NW1*
† *Research and Laboratory Services Division, HSE, Sheffield.*

0033–7722/81/040151 +19 $1.50/0

There were, however, large differences between the reported threshold levels, as well as doubts concerning the validity of using them for assessing practical hazards. The investigations described here were carried out primarily to provide answers to the following questions:

(i) What types of discharges can be produced from tuned loop structures, and can they be modelled in the laboratory using equivalent circuits?

(ii) What parameters can be used to characterize the incendivity of such discharges?

(iii) What are the 'correct' ignition thresholds for 50 Ω resistive sources and can they be used for hazard assessment?

2 Discharges from a Tuned Loop Structure

In order to find out what types of discharge occurred at make and break contacts across the tuning capacitor in a pipe loop tuned to resonance, experiments were carried out using a 3 m square of 2·54 cm (1 in) diameter copper pipe excited in a field of about 10 V/m at 692 kHz close to the BBC Moorside Edge transmitter. Oscillographic observation showed that the discharges consisted of a sequence of impulsive capacitive discharges of the tuning capacitor separated by the time intervals needed to recharge the capacitor.

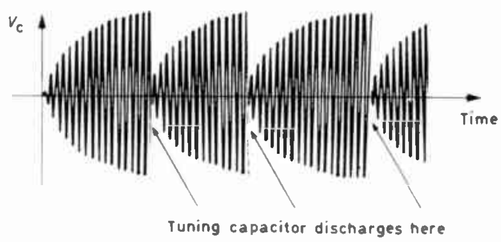


Fig. 1. Typical discharge oscillogram from a tuned loop structure.

A typical oscillogram is shown in Fig. 1, in which it can be seen that the breakdown level varies somewhat from one impulsive discharge to the next.

3 Equivalent Circuits for Loop Structures at H.F.

It is well known[8] that electrically small loop aerials can be modelled by means of a generator driving a series-connected R, L, C circuit. R represents the sum of radiation and loss resistances, L the loop inductance, and C the capacitance across a break in the loop. The generator voltage V depends on the loop area and the exciting field intensity. When the loop is tuned to resonance the voltage across the tuning capacitance is given by

$$V_0 = QV \sin \omega t$$

where $Q = \omega L/R$ and $f = \omega/2\pi$ is the resonant frequency.

When discharges were produced from tuned LCR circuits driven by a generator, the discharges produced were found to be of the same form as those from the irradiated tuned loop structure described in Section 2.

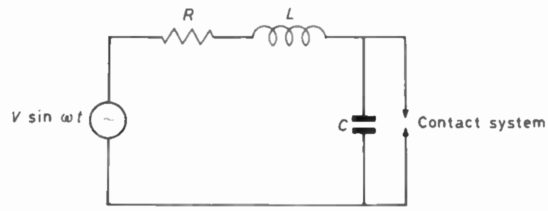


Fig. 2. Circuit for producing discharges from small loop aerial equivalent circuit.

The circuit arrangement used is shown in Fig. 2, and the behaviour illustrated in Fig. 1 has been observed in equivalent circuits with Q values from 4 to 100 and for frequencies up to 10 MHz. This means that such directly driven equivalent circuits can be used to carry out ignition experiments in the laboratory in order to model the practical situation in which tuned pipe loops are excited by radio transmissions. It should be noted, however, that electrically large loops cannot be modelled in this way, since such a simple equivalent circuit is no longer applicable. However, the simple approach possible for small loops provides a useful insight into the more complex conditions that arise in self-resonant situations.

4 Power and Energy Transfer to Discharges

The mean power P_d dissipated in a discharge of the type shown in Fig. 1 can be calculated as follows. In most cases the tuning capacitor discharges to almost zero volts each time a discharge occurs. The discharge energy associated with each impulsive discharge is therefore close to $\frac{1}{2}CV_b^2$, where V_b is the capacitor voltage at breakdown. The time constant for the exponential envelope of the recharging curve is $Q/\pi f = 2L/R$.

It can then be shown that

$$P_d = \frac{-RC\,V_b^2}{4L \ln(1 - V_b/QV)}$$

For a matched resistive load the power, P_m, dissipated is $P_m = V^2/8R$, and

$$P_d/P_m = \frac{-2\,(V_b/QV)^2}{\ln(1 - V_b/QV)}$$

P_d/P_m has a maximum value of about 0·8 when $V_b/QV = 0{\cdot}7$, and exceeds 0·6 when V_b/QV is between about 0·4 and 0·95. P_d is therefore relatively insensitive to variations in V_b and, since V_b is usually within the above range, the discharge provides quite a good match to the source, and can dissipate up to 80% of the available power.

5 Theoretical Effect of the Ignition Initiation Time on the Incendivity of Discharges from Tuned Loops

The discussion above indicates that discharges from tuned loops consist of a series of capacitive discharges separated by time intervals that depend on the time constant $Q/\pi f$. There is considerable information already available on the incendivity of individual capacitive discharges, but one unknown factor is the co-operative effect of discharges separated by times that are short compared to the ignition initiation time. This initiation time (t_c) is known from other experiments to be about 100 μs for methane/air mixtures, and about 20 μs for hydrogen/air. If the individual discharges occur at intervals greater than t_c they can be regarded as separate events, and a knowledge of the maximum stored energy $\frac{1}{2}CQ^2V^2$ released in one event is sufficient for assessing incendivity. However, if the individual discharges are closer together incendivity is assessed on the basis of the maximum energy that can be dissipated in the time interval t_c.

The maximum energy E_c that such a discharge sequence can dissipate in a time interval t_c is given by

$$E_c = 0{\cdot}8\,P_m t_c + \tfrac{1}{2}C\hat{V}^2 \qquad (\hat{V} = QV),$$

since the sequence of discharges may be preceded, in a very short time interval, by a single discharge of the capacitance from the maximum voltage level. Such discharge behaviour would be expected to occur as two contacts approach. The initial breakdown is likely to be at a voltage near the maximum steady-state voltage, but subsequent individual breakdowns will probably occur at lower voltage levels. E_c can also be expressed as:

$$E_c = 0{\cdot}8\,\frac{\hat{V}^2}{8Q^2R}\cdot t_c + \tfrac{1}{2}\,C\hat{V}^2$$

This formula can be used to provide an assessment of the threshold peak ignition voltage if values can be assigned to R, C, Q, t_c and E_c. It also indicates that when the stored energy is negligible, the ignition threshold is characterized by the power available to a matched load.

6 Ignition Experiments with D.C. Circuits and Tuned Loops

6.1 Ignition Experiments with D.C. Capacitive Circuits

Some ignition experiments were carried out with d.c. capacitive circuits in order to simulate the sequence of capacitive discharges from a tuned loop. The time-constant of the circuit (equivalent to $Q/\pi f$) was changed by varying the charging resistance for a number of capacitance values. The minimum source voltages (equivalent to QV) needed to obtain ignition of hydrogen, ethylene and methane/air mixtures were determined as a function of the capacitance value and the time constant. Briefly, the results showed that the ignition initiation time t_c was about 100 μs for methane and ethylene and about 30 μs for hydrogen. The stored energy values required for ignition with large values of time-constant varied with the value of capacitance, and were in the range 60–80 μJ for hydrogen, 450–650 μJ for ethylene and 1·5 to over 4 mJ for methane. For time-constants less than t_c the stored energy values fell continuously as the time-constant was reduced, but the value of available power (equivalent to P_m) rose steadily and did not reach a steady value, as might be expected. This may be due to increased flame-quenching effects as the circuit voltage falls, or to difficulty in maintaining a discharge sequence for a period equal to t_c at the lower voltages.

6.2 Ignition Experiments with Tuned Loops

In the following experiments the loop consisted of a 3 m square made from 2·54 cm (1 in) diameter steel conduit pipes. The loop was broken at the mid-point of one side; the tuning capacitor (a 1000 pF variable air dielectric plus, where necessary, additional fixed mica capacitors designed for radio frequencies) and the breakflash apparatus, were connected across the break in the pipe. The breakflash was a basic IEC 79–3/BS 5501: Part 7[9] design, modified so that the contact pressure was adjustable. Voltages were measured by means of a 100:1 or 10:1, 10 MΩ probe and a Tektronix oscilloscope Type 7623 (bandwidth about 100 MHz), and currents with a Tektronix Type P6016 current probe with a passive termination which is sensibly flat up to 15 MHz. Power was fed into a wire loop about 0·5 m away from the steel loop using a 300 W ENI Linear Power Amplifier Type A300, and the steel loop was tuned to resonance by adjusting the capacitance across the breakflash apparatus with the current and voltage probes connected. The value of capacitance was measured with a Wayne Kerr Type B621 Bridge (which measures at 1592 Hz); the steel loop was disconnected for capacitance measurements, but the breakflash apparatus (open-circuited) and the oscilloscope probes were left connected. For some experiments the cadmium disk electrode in the breakflash apparatus was replaced with an aluminium or rusty steel disk.

Values of Q and of the power P_m that the loop could transfer to a matched resistive load were derived from measurements of the peak-to-peak voltage V_{pk-pk} across the open-circuited breakflash, the peak-to-peak current $I_{sc\,pk-pk}$ with the breakflash short-circuited and I_T, the tuned current with the breakflash open-circuited.

The lowest levels at which ignition was obtained are given in Table 1 together with calculated values of $Q, Q/\pi f, P_m$ and $\frac{1}{2}CV_{pk}^2$, where $V_{pk} = \frac{1}{2}V_{pk-pk}$. For the results at 5·2 MHz and 6·8 MHz no Q values are quoted because at these frequencies the stray capacitance of the loop is large compared with the tuning capacitance, and it is not considered meaningful to apply the lumped circuit formulae in these circumstances. The only reliable measurement at these frequencies that could be made at the time was the peak-to-peak voltage across the breakflash apparatus needed for ignition. The measurement of the corresponding current when the breakflash was short-circuited also presented difficulties. Even at 2·08 MHz the tuning capacitance is some 100 pF less than expected from the values at lower frequencies, so that the calculated values at this frequency should be regarded as approximate.

Table 1

Data from tuned loop experiments indicating the lowest voltage at which ignition of ethylene/air was obtained with an RLSD-modified IEC-type breakflash apparatus.
RS = rusty steel; Al = aluminium; Cd = cadmium

Frequency MHz	Tuning Capacitance pF	$I_{Tpk\ pk}$ A	$I_{sc\ pk-pk}$ mA	Q	$Q/\pi f$ μs	V_{pk-pk}	P_m watts	$\frac{1}{2}CV_{pk}^2$ μJ	Disk Electrode Material
0·41	9100	10·2	610	16·6	13	350	6·7	139	RS
						350	6·7	139	Al
						550	16·5	344	Cd
0·50	6110	9·6	580	16·5	10·5	400	7·3	122	RS
						500	11·4	190	Al
						530	12·8	214	Cd
0·85	2100	8·4	380	22·1	7·8	700	10·5	129	RS
						700	10·5	129	Cd
1·24	1085	8·0	380	21·0	5·4	800	9·5	87	RS
						750	8·3	76	Al
						800	9·5	87	Cd
2·08	266	5·2	350	14·8	2·3	840	9·2	23·5	RS
						880	10·1	26	Cd
5·2	75	0·1				600			RS
6·8	24	0·15				630			RS
						700			Al
						700			Cd

A number of features of the results in Table 1 are discussed below; it should be remembered that these data relate only to the ignition of ethylene/air mixtures:

(i) It appears that rusty steel is substantially more sensitive than cadmium when the value of V_{pk-pk} for ignition with cadmium is less than about 700 V. In the experimental conditions employed these large differences in sensitivity occur only at the two lowest frequencies where the effective source resistance is lower. This raises the question of whether it is a voltage or frequency effect; this is discussed in more detail later when it is concluded that it is probably a voltage effect related to the source resistance.

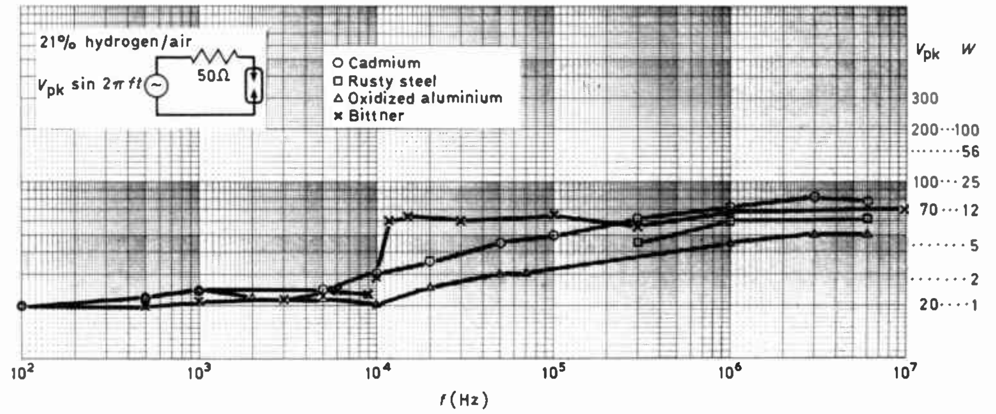
(ii) The matched resistive load power P_m required for ignition appears, if anything, to increase with decreasing frequency for cadmium, whereas the opposite tends to be the case for rusty steel. If the cadmium figures are compared with those for a similar capacitance value and time constant in the d.c. experiments described in Section 6.1, there is reasonable agreement; e.g. at 1·24 MHz and 1085 pF, a power of 9·5W was required with $Q/\pi f = 5{\cdot}4\ \mu$s, whilst 11 W was required for 1000 pF and $RC = 6\ \mu$s in the d.c. experiment.

The matched resistive load powers needed for ignition lie in the range from 6·7 to 16·5 W. If the initiation time t_c for ethylene is taken as 100 μs then, using the equation for E_c in Section 5, the maximum discharge energy over a period of 100 μs is in the range of 675–1664 μJ. The lower figure is, in fact, quite close to that for ignition by a single capacitive discharge. Figures as high as 16·5 W may occur because, if the voltage available is insufficient, the discharge sequence made up of a series of individual capacitive discharges may not last for as long as 100 μs, so that the maximum actual discharge energy is limited by the lack of voltage. If the effect of rusty steel is to favour breakdown at lower voltages than cadmium, then this would explain why rusty steel is more sensitive than cadmium for the lower source resistance circuits, but it must be stressed that this is conjecture at this stage.

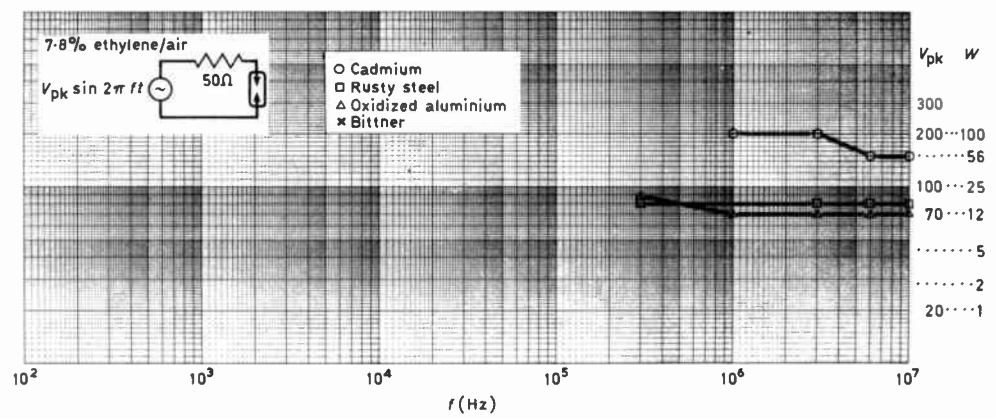
(iii) On the basis of 100 μs integration time for ethylene, and taking a capacitance ignition energy figure of about 500 μJ, it would not be expected theoretically that ignition would be obtained in tuned loop experiments with small values of $Q/\pi f$, say less than 5 μs, unless the power available to a matched resistive load exceeded about 6 W. It also appears from experiments reported in the next Section that a similar value of power is needed for ignition with a loop tuned by its own distributed capacitance, but these results need to be confirmed.

6.3 Comparison of Ignition Thresholds for Different Gases

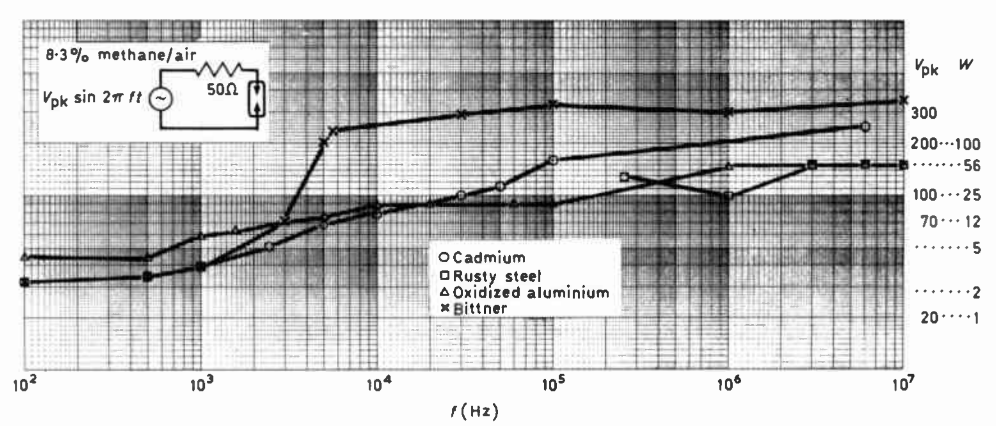
In order to provide a comparison between incendive power levels for hydrogen, ethylene and methane, ignition experiments were carried out with a self-tuned loop that had a lower effective resistance than that used for the results in Table 1. The self-resonant frequency was 7·1 MHz and the effective source resistance was about 700 Ω. With a rusty steel disk in the breakflash ignition of hydrogen was obtained at 200 V pk–pk (1·9 W), ethylene at 400 V pk–pk (6·9 W) and methane at



(a) 21% hydrogen/air mixture



(b) 7·8% ethylene/air mixture



(c) 8·3% methane/air mixture

Fig. 3. Minimum ignition voltage for a 50 Ω resistive source as a function of frequency and electrode material for various gas mixtures (IEC-type breakflash).

W indicates the maximum power to a matched 50 Ω load ($W = V_{pk}^2/400$).

500 V pk–pk (10·5 W). The power levels quoted should be regarded as approximate because of the difficulties experienced in measuring currents in the loop.

7 Ignition Experiments with Resistive R.F. Circuits

Ignition experiments have also been carried out with radio frequency sources with a 50 Ω source impedance, care being taken to ensure that the 50 Ω figure was, as far as possible, purely resistive.

7.1 Experimental Details

In the frequency range below 100 kHz a 1 kW Savage Type KRF amplifier was used. The output impedance of this amplifier is low and typically less than 5 Ω up to 100 kHz. The output from the amplifier was connected to the breakflash apparatus via a 2 m length of cable, and a 50 Ω non-inductive wire-wound resistor was connected in series, directly at the breakflash apparatus, in order to provide a 50 Ω resistive source. Oscillographic observation of the behaviour of this 50 Ω source when it was switched with the breakflash apparatus showed that it was virtually free from undesirable reactive effects.

For frequencies of 300 kHz and above, an ENI A300 linear amplifier was used. This amplifier claims to have a 50 Ω resistive output impedance and the checks made largely substantiate this claim.

All voltage and current measurements were made with the Tektronix equipment described in Section 6.2. Additionally, for frequencies up to 70 kHz the discharges that actually caused ignition were examined by means of a two-channel (normally voltage and current) analogue/digital storage and display system[10] sampling at 1 MHz and storing 2048 8-bit words. The information obtained confirmed that, up to 70 kHz, the maximum frequency for which reasonably accurate records can be obtained from the storage system, there was no anomalous behaviour of the power source that could have contributed to the observed ignition behaviour. Ignition was found to be associated with arc-type discharges with voltage levels up to about 20 V.

7.2 Experimental Results

The lowest peak voltages at which ignition was obtained (normally in a period of at least 400 revolutions of the breakflash) were determined in the most easily ignited mixtures of hydrogen (21%), ethylene (7·8%) and methane (8·3%) with air. The results are plotted in Figs 3(a), (b) and (c) for a cadmium disk electrode, and also over parts of the frequency range for aluminium and rusty steel electrodes. Bittner's figures[4] are also shown where available.

7.3 Discussion of Results for Resistive Circuits

7.3.1 Power transfer from resistive sources

The power transfer from a resistive source into a discharge can be analysed in the following way. At frequencies up to at least 10 MHz, the discharges take the form of arcs, provided the source open-circuit voltage is less than about 300 V peak. An arc forms during one half cycle, extinguishes when the current reverses and then restrikes in the opposite direction during the next half-cycle. During any one half cycle the arc voltage is approximately constant and typically has a value in the range of 10–20 V, the value depending on the electrode materials used and the separation between the electrodes.

If it is now assumed that the arc voltage V_a is, in fact, constant and that the arc forms as soon as the source voltage reaches V_a, it is possible to calculate the average power, P_{arc}, dissipated in the discharge.

It can be shown that

$$P_{arc} = \frac{2V_pV_a}{\pi R}\left\{\sqrt{1-\left(\frac{V_a}{V_p}\right)^2}-\frac{V_a}{2V_p}\left(\pi-2\sin^{-1}\frac{V_a}{V_p}\right)\right\}$$

whereas the power dissipated in a matched resistive load is $P_m = V_p^2/8R$; V_p is the peak voltage of the source and R the source resistance.

Figure 4 shows the way in which the mean discharge power from the formula above varies with the arc voltage for a range of source voltages. In general, for frequencies up to 10 MHz the arc voltages observed experimentally lie in the range from about 10 to 20 V. In these circumstances for the higher voltage sources the power transfer to the discharge from the resistive source is well below that into a matched load, e.g. for a source voltage

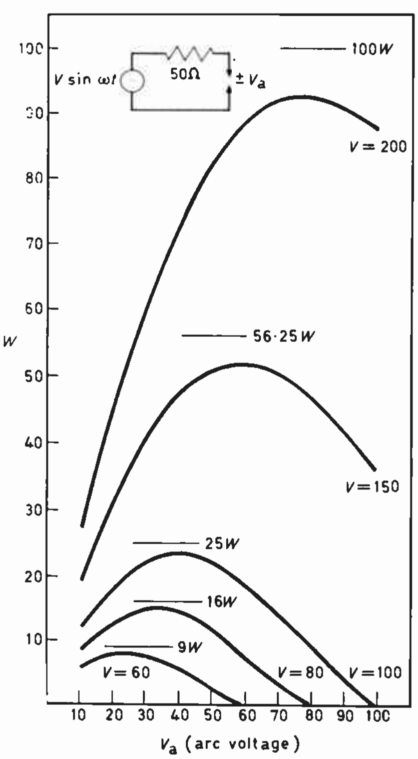


Fig. 4. Mean discharge power *W* as a function of arc voltage for a 50 Ω resistive source.

of 200 V peak the mean discharge power is in the range of 24–42 W compared with 100 W into a matched load. This perhaps provides one reason for the high matched load levels required for ignition from resistive sources. In practice many arcs do not form when the supply voltage reaches V_a, but only when it exceeds V_a by a substantial amount. This effect will tend to reduce further the efficiency of power transfer from a resistive supply into an arc discharge. (Note that if the breakflash capacitance is significant, such restrike behaviour will also transfer power because the stored energy in the capacitance is dissipated in the arc when it restrikes.)

A further reason is thought to be the inability of the discharge to continue for a time comparable to the ignition initiation time, so that the discharge energy is limited to a value less than that expected from the product of mean power and initiation time. Bittner's results for source resistances higher than 50 Ω indicated that much lower matched load powers are then capable of causing ignition,[4] presumably because the higher voltage for a given power level is capable of maintaining the discharge for a longer time.

7.3.2 Effect of electrode materials

With a 50 Ω source the use of a rusty steel or aluminium electrode gives substantially lower levels for ignition than a cadmium electrode. This is probably because the more sensitive materials give more stable and long-lived discharges, but other factors, such as different arcing voltages or dielectric and chemical effects, may also be involved. These materials are, however, less sensitive than cadmium in d.c. resistive circuits.

7.3.3 Comparison with previous results

Earlier determinations of ignition threshold values for 50 Ω circuits using a cadmium electrode have produced very widely differing results. Howson *et al.*[5], on whose results the draft revision of BS 4992[3] was based, found ignition threshold powers of about 50 W for hydrogen/air and 500 W for propane/air in the frequency range 1–10 MHz. This is thought to be due to the properties of the power source employed, and its slow recovery characteristics immediately following the removal of a short circuit. The more recent experiments of Howson *et al.*[6] were made with a better behaved 50 Ω source, and agree quite well with the present findings. Bittner[4] used a cadmium disk electrode and his results for hydrogen are also in reasonable agreement except that he found a pronounced low-frequency step at about 10 kHz rather than a general increase in ignition threshold as the frequency increased up to around 1 MHz.

8 Comparison of Results for Resistive and Tuned-loop Circuits

It is clear that in tuned-loop experiments much lower ignition threshold powers are found than in 50 Ω circuits, although higher voltages are needed. This is a reflection of the higher source resistances associated with the tuned *LCR* circuits used.

Recent work by the writer, to be published later, has shown that as the source resistance increases for resistive circuits, the voltage required for ignition increases but the available power falls, and tends to a relatively constant value for source resistances greater than about 1000 Ω. The same pattern emerges for tuned loop sources, and for a given source resistance approximately the same ignition threshold voltages and powers are found in the range above a few hundred ohms where the results can be compared.

In order to assess incendivity in a given practical situation, at first sight it would appear that the source resistance would have to be known. However, the source resistances of practical examples of tuned-loop structures tend to be quite high, and up to a few thousand ohms. This means that the roughly constant ignition threshold power level for such high impedance circuits can be used as a basis for practical assessment purposes. It is quite clear that the results for 50 Ω sources are inappropriate unless structures with a correspondingly low source resistance are involved.

9 Conclusions from M.F./H.F. Results

(i) It has been shown that discharges produced by making and breaking contact across the tuning capacitor of an electrically small tuned-loop structure excited by a radio transmitter consist of a sequence of impulsive discharges of the tuning capacitor.

(ii) The practical situation can be modelled by a simple tuned *LCR* circuit.

(iii) Available power to a matched load is the parameter which best characterizes the incendivity of discharges from tuned loops, which generally have a high effective source resistance.

(iv) Ignition threshold voltages and powers have been determined for a 50 Ω resistive source. The values obtained are not appropriate for hazard assessments on tuned loop structures because their effective source resistance is generally much greater than 50 Ω.

(v) The ignition threshold powers appropriate for assessing practical tuned loop situations are about 2 W for hydrogen/air, 7 W for ethylene/air and 10 W for methane/air. From what little evidence is available, these power levels are also appropriate for large self-tuned loops.

Part 2 INCENDIVITY OF DISCHARGES FROM DIPOLES IRRADIATED BY PULSED RADAR TRANSMISSIONS

R. J. Loveland, R. Tomlinson and D. W. Widgington

This part describes a series of experiments performed to determine the minimum field intensities at which incendive sparks could be produced from metal pipes when irradiated by pulsed radar transmissions.

The revised draft British Standard 4992 : 1974[3] gives some guidance on the threshold field strengths which might produce incendive discharges if the metal structures of interest behave as high gain long dipoles. However, the use of the relevant graph in this standard (Fig. 1 of Ref. 3) for pulsed radar transmissions is open to criticism. In the frequency range of interest the graph is based only on an interpolation between a set of points at a few hundred megahertz and one point at 9 GHz. In the experiments from which the few hundred megahertz points were derived, hydrogen-air mixtures were ignited by directly connecting a make-and-break contact system, hereafter called a breakflash, to a continuous wave (c.w.) transmitter. The 9 GHz point was derived from a set of experiments in which various gases were ignited in a microwave-cavity breakflash directly connected to a pulsed microwave transmitter.[11] These experiments are only indirectly related to the practical case of metalwork irradiated by pulsed radar transmissions. One other reference was discovered[12] in which the National Aeronautics and Space Administration (USA) had tried unsuccessfully to ignite hydrogen by placing a dipole system in the field from a low power 600 MHz continuous wave transmission.

Some preliminary tests were carried out using the facilities of the Admiralty Surface Weapons Establishment (ASWE) in which two types of breakflash were directly connected to a pulsed 220 MHz transmitter.[13] The results from these tests are discussed in Section 12.1.

In view of the fact that the majority of the work so far has been carried out with transmitters directly connected to a breakflash, it was considered worthwhile to perform a series of tests (over one hundred in all), in which the various types of aerial breakflash described in Section 10 were irradiated by pulsed radar transmissions. The metal pipes and the associated breakflash apparatus were set up in a dipole configuration so that standard antenna theory could be applied to estimate the extractable power.

The experiments were carried out with the co-operation of the Ministry of Defence who made available the Radio Frequency Environment Generator (REG) facility at the Aeroplane and Armament Experimental Establishment (AAEE), Boscombe Down, Wiltshire. This enabled these aerial breakflashes to be irradiated with pulsed fields at frequencies of between 200 MHz and 5·5 GHz, and c.w. at 9 GHz.

10 Experimental Arrangements

10.1 REG Test Facility

This consists of a concrete pad approximately 50 m × 110 m encircled by a set of radar aerials, each aerial being fixed in position and giving a separate radar beam of known characteristics. The 200 MHz aerial was situated on the pad and the other aerials were situated off the pad at distances such that the power flux density at the nearest edge of the pad was 500 W/m^2 or less. Table 2 gives details of the transmitters, aerials and outputs used during these tests.

Table 2

Radar sources

Transmitter	Frequency	Maximum mean power flux densities	Output	Aerial
Marconi P Band 220–225 MHz	220 MHz	20–40 W/m^2	Pulsed, linear horizontal polarization, 900 W average, 450 kW peak power. Pulse width 8 μs, rep rate 250 p/s	8m wide single bedstead aerial
600 S 2300–3700 MHz	3112 MHz	700–800 W/m^2	Pulsed, circular polarization, 3·38 kW average, 2·25 MW peak power. Pulse width 5 μs, rep rate 300 p/s	4 m wide 'orange peel' dish
600 S 5000–5900 MHz	5500 MHz	200–400 W/m^2	Pulsed, circular polarization, 1·5 kW average, 1 MW peak power. Pulse width 5 μs, rep rate 400 p/s	4 m wide 'orange peel' dish
86X2 7900–10700 MHz	8730 MHz	1000 W/m^2	c.w., circular polarization, 1·4 kW average power	2 m diameter circular dish

In order to vary the power flux density at the breakflash, the distance of the aerial breakflash from the transmitting aerial was altered as required. In addition the power output from the 220 MHz transmitter could be varied. The aerial breakflash system was always placed in the centre of the beam and its orientation determined relative to the direction of the beam.

10.2 Power Flux Density Measurements

Power flux density measurements were made using Narda instruments[14] with a specified accuracy of 0·5 dB. At 220 MHz a Narda 8616 meter with a model 8631 isotropic probe was used; at 3 GHz and above a Narda 8323 isotropic probe with an 8316 meter was used.

All the power flux densities at 220 MHz in these experiments were below the biological limit of 100 W/m^2 (10 mW/cm^2) but at 3 GHz and above, most fields were greater than this limit. Where it was necessary to measure power flux densities in excess of this limit, this was done by one of the military personnel who were authorized to go into fields of up to 500 W/m^2 for short periods. The field measurement of 600 W/m^2 in the 9 GHz tests was measured with only the Narda probe itself exposed to this high field which was produced in a narrow beam.

The field distribution in front of the 220 MHz aerials was checked for uniformity in the absence of any aerial breakflash system. No distinctive interference patterns, field nulls or peaks could be found. The field was found to decrease smoothly as the distance from the aerial increased and to increase smoothly as the probe was moved vertically upwards from the ground to a height of 2·4 m. It was also found that the fields just in front of and at the same height as the aerial breakflash system, i.e. at a position slightly nearer to the transmitting aerial, correlated well with fields found at the test position without the breakflash. When the breakflash was not removed, the minimum field just in front of the system was recorded as the relevant field. For the tests of 220 MHz with the RLSD copper aerial breakflashes the field was measured with the aerial removed.

Major temporal changes in the power flux density were noted, especially at 220 MHz, as the result of changing weather conditions. Therefore the power flux density was measured either immediately before, during or immediately after each test.

The power flux densities for the 3 GHz, 5 GHz and 9 GHz tests were averages in the vicinity of the breakflash. Once again at these frequencies there was no indication of any significant nulls or peaks, but with the longer dipoles there was a significant change in power flux density along the beam from one end of the dipole to the other.

It should be noted that the effective power flux density for a horizontal dipole in a circularly polarized field (3, 5 and 9 GHz transmissions) is only one-half of that measured with an isotropic probe.

10.3 Aerial Breakflash Equipment

Various dipole arrangements were used to extract power from the radiated field, and a make-and-break contact system was placed between the two halves of the dipole in order to obtain electrical discharges. The contact system was immersed in a flammable gas mixture, so that it was possible to determine whether or not the discharges caused ignition. Details of the arrangements used are as follows.

10.3.1 RLSD systems

The types as described below were used, both being 1·5 m off the ground on insulating wooden supports.

(a) *RLSD copper pipe dipole with IEC-type contact system* (*Fig.* 5). The dipole was formed by two 30 cm long 5 cm diameter copper pipes. Each pipe could be extended by a screwed coupling to a length of 100 cm. For some experiments a 15 cm diameter flange was fixed to each pipe so that the flanges were at the centre of the dipole. The contact system consisted of a 0·2 mm diameter steel, copper or tungsten wire, which was attached to a threaded rod running through one half of the dipole, and a grooved cadmium disk driven by a small electric motor at about 1 rev/second, via a shaft running through the other half of the dipole. The motor was electrically insulated from the driven shaft. The contact pressure between the wire and the rotating disk could be adjusted by means of the threaded rod. The contact system is very similar to that used for intrinsic safety testing as described in BS5501: Part 7: (EN50 020).[9] The flammable gas mixture was fed continuously through a flame trap and a pipe running through the half of the dipole, to which the wire contact was fixed, in order to ensure that the gas mixture emerged into the region of the contact system. This region was enclosed by polythene sheet, or a perspex tube, and adhesive tape so that a suitable ignition chamber was formed around the contact system. Ignition was detected by the noise of the explosion.

(b) *RLSD steel pipe dipole with IEC-type contact system*. The basic design follows almost exactly that of the copper pipe dipole. The steel pipe used was 2·5 cm diameter conduit. The lengths used were again 30 cm and 100 cm for each half of the dipole, and the flanges, which could be removed, were 22·5 cm in diameter. The contact system was identical except that the cadmium disk was of smaller diameter in order to fit within the pipe diameter. The flammable gas was fed in the same way as described above.

Unless otherwise stated, the distance between the flanges in both systems was maintained at 4 cm.

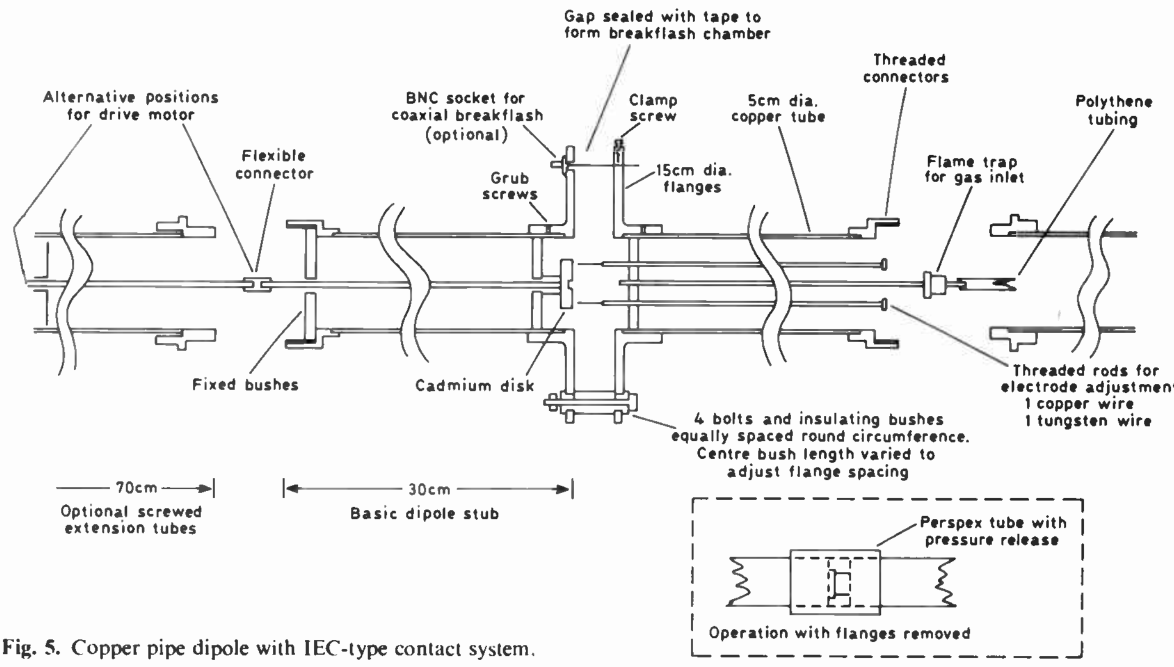


Fig. 5. Copper pipe dipole with IEC-type contact system.

10.3.2 ASA pipe systems

Horizontal dipoles were produced by setting a pair of either 10 cm diameter or 15 cm diameter, 2 m long, flanged at one end, American Standards Association pipes, 1·5 m off the ground on insulated wooden supports. The pipe flanges were 24 cm and 28 cm diameter respectively for the 10 cm and 15 cm diameter pipes.

The insides of the pipes were sealed a few centimetres away from the flanges by mahogany plugs and flammable gas–air mixtures were fed into the flanged area via a 2BA hole tapped in one of the pipes between the plug and the flange. The escape of the flammable mixture was restricted by enclosing the flanges in a polythene tube sealed onto the pipes by means of strong elastic bands. The gas–air mixture was tested for flammability by inserting a small spark plug inside the polythene tube and igniting the gas using this mechanism.

Initially the experiments were carried out with the flanges bolted together or just separated by a 2 mm thick asbestos gasket and the pipes rocked together and apart. However, it was found that in order to produce incendive sparks an arrangement as shown in Fig. 6 had to be used. A tightly fitting brass bush was inserted into one of the bolt holes on the flanges and through the centre of this bush was passed a 0·3 cm diameter copper rod which had either a blunt end, an end sharpened to a point or a small steel panel pin soldered onto it. This copper rod, plus point, was spring-loaded so as to bridge the gap between the flanges and sparks were produced by moving the rod by pulling on a string so contact was made and broken with the second flange. No significant variation in incendivity was found using any of the three bridging devices and the majority of the experiments were carried out using the steel panel pin system. Occasionally a screwdriver with a tip was used to bridge the flanges in a similar manner. Unless otherwise stated the distance between the flanges was maintained at 4 cm.

For some experiments with the ASA pipes the contact system consisted of a miniature 'coaxial' breakflash as used in the direct connection experiments at ASWE.[13] This breakflash was connected across the flanges by means of leads some 6 cm in length, the breakflash being placed within the pipe-dipole. The 'coaxial' breakflash (Fig. 7) is not coaxial in the conventional sense, but was designed so that a breakflash with low inductance and capacitance could be plugged directly into a coaxial socket. It is constructed from a 50 Ω in-line module case (Radiospares) fitted with a BNC socket at one end. The centre contact of the socket is connected to a 13 mm diameter cylindrical cadmium disk with a roughened surface and two longitudinal grooves; the disk, which is placed within the in-line module case, is rotated by an externally-mounted motor via an insulating shaft, against a 0·2 mm diameter tungsten wire having a length of about 5 mm which is connected to the outer of the in-line module case. The contact pressure is adjustable. Flammable gas is fed continuously into the case through an external flame trap, and part of the case is cut away so that any sparking can be observed by eye. The opening is covered with transparent adhesive tape and ignition was detected visually and by the noise of the explosion.

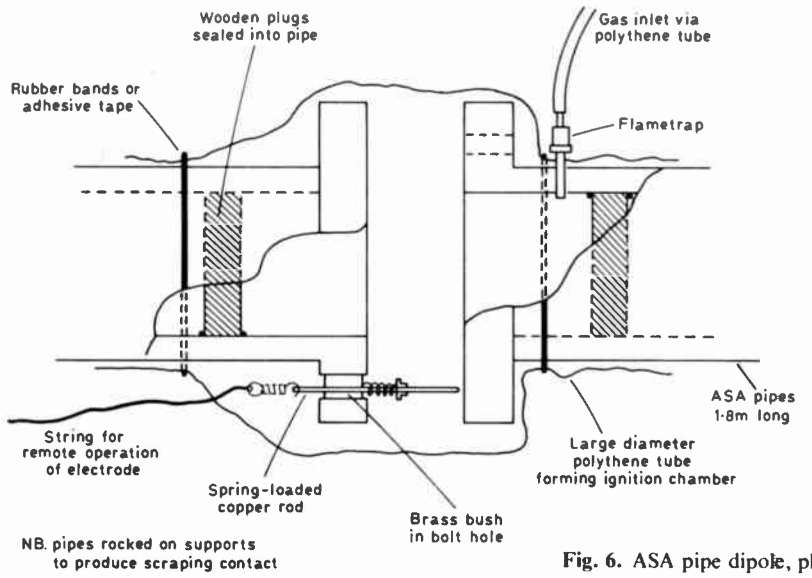


Fig. 6. ASA pipe dipole, plus contact system.

10.3.3 Flammable gas mixtures

The flammable gas mixtures used in the ignition experiments were those mixtures of hydrogen (21%), ethylene (7·8%) or methane (8·3%) with air most easily ignited by electrical discharges. A continuous flow system was employed, the gases and air being fed separately from high-pressure cylinders via a pressure regulator and needle valve through to previously calibrated flow meters. The gas and air were mixed close to the flowmeters and then fed through a polythene pipe and a flame trap into the breakflash. Remotely operated solenoid valves were fitted to divert the gas flow to atmosphere after an ignition in order to prevent a continuous flame burning within the breakflash. The total flow rates were 6–10 l/min.

10.4 Power and Current Measurements

10.4.1 Power measurement

A specially adapted electro-explosive device (EED) was supplied by the Aeroplane and Armaments Experimental Establishment (AAEE). The device was fitted with a thermocouple and various electronic and fibre optic systems and was calibrated to enable a remote read-out of the power absorbed. It was fitted inside the ASA pipes and connected across the flanges using 6 cm long wires.

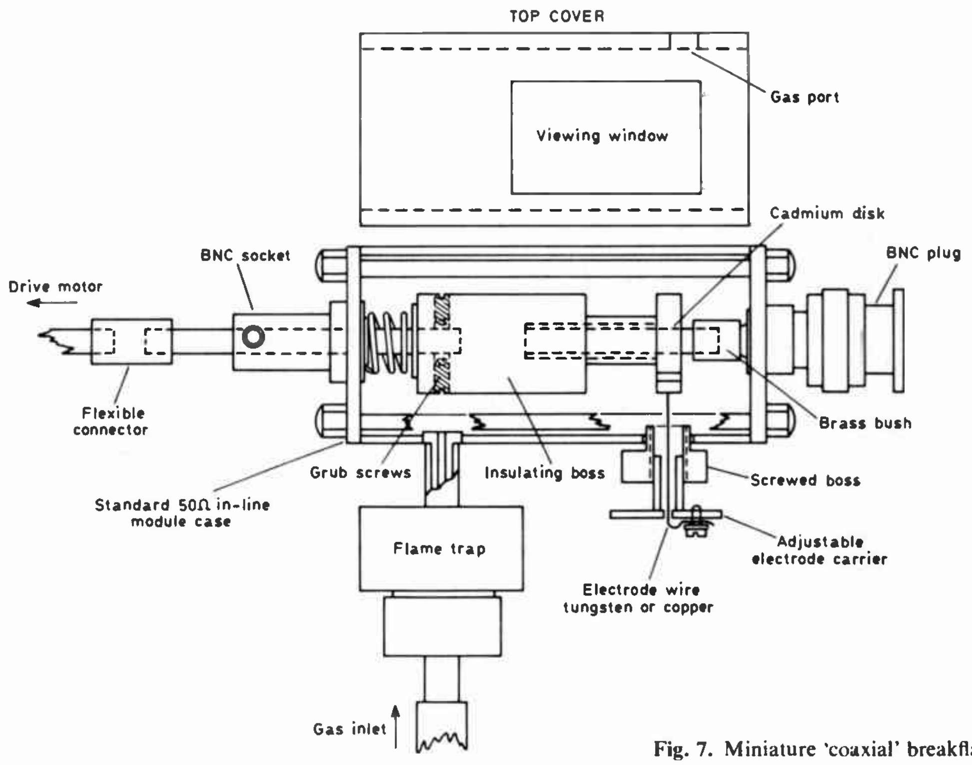


Fig. 7. Miniature 'coaxial' breakflash.

All of the measurements with this device were taken whilst the pipes were irradiated at 220 MHz. The impedance of the device was not known at 220 MHz but was quoted by AAEE as 50(0·016–j 0·015) Ω at 1 GHz and 50(0·026–j 0·050) Ω at 3 GHz.

In one experiment the device was connected between the hook and chassis of a 19 m jib stabilized telescopic crane, whilst the crane was 60 m from the 220 MHz aerial. No absorbed power could be detected.

10.4.2 Current measurement

A special current measuring system for use up to 250 MHz was supplied by AAEE. The 15 cm diameter ASA aerial-breakflash system was set at 30° to the beam direction with 4 cm between the flanges and the flanges were shorted by either a 1 cm diameter bolt or high stability carbon resistors of known value. The current in the shorting device was measured by encircling it by a current measuring toroid with a transfer impedance of 7 Ω. The signal from the toroid was fed by direct connection into a screened cylinder which contained the electronics and fibre optic conversion system. The outputs from the cylinder were two 50 m long fibre optic leads which were taken back into a logic unit, and the output from the unit was displayed on a wide-band oscilloscope.

11 Experimental Results

11.1 Aerial Breakflash in the Beam from one Radar Source

The minimum power flux densities required to produce ignition for each type of aerial breakflash at different frequencies and with different gases are shown in Table 3. These values were obtained by initially determining the most favourable orientation for ignition and then moving the breakflash along the centre of the radar beam and at 220 MHz, adjusting the power of the transmission. Table 3 also shows the most favourable orientation in each case, the angle shown being the one between the beam direction and the dipole main axis. An illustration of how critical orientation could be was given when attempts were made to obtain an ignition of hydrogen at 3 GHz with the RLSD 60 cm, unflanged, copper system. In the position where the power flux density was 400 W/m² (compared with the minimum value for ignition of 175 W/m²) ignitions only occurred when the main axis of the dipole was within 10° of the most favourable orientation.

The effect of orientation was confirmed by measuring the power absorbed in the modified EED mounted in the 15 cm ASA pipe system. The power absorbed increased by approximately 50% when this system was moved from a position with its axis normal to the 220 MHz radar

Table 3

Ignition threshold mean power flux densities

Aerial Breakflash		(ignition/no ignition) mean power flux densities in W/m² and most favourable orientation angle between dipole main axis and radar beam direction			
		220 MHz	3112 MHz	5500 MHz	8730 GHz
(A) HYDROGEN					
RLSD 60 cm Copper	with flanges	(2/1·5) 90°	(–/500)	(–/350)	(–/600)
	without flanges	(0·4/0·3) 90°	(175/140) 25°	(–/350)	(–/600)
RLSD 200 cm Copper	with flanges				
	without flanges	(0·6/0·5) 45°	(500/–) 0°	(–/350)	
RLSD 60 cm Steel	with flanges	(3/–)			(–/600)
	without flanges				(–/600)
10 cm ASA pipes (4 m length)		(1·5/–) 25°	—	—	—
15 cm ASA pipes (4 m length)		(1·5/–) 25°	—	—	—
(B) ETHYLENE					
RLSD 60 cm Copper	with flanges	(18/–)			
	without flanges	(2·5/2·5) 90°	(–/500)	—	—
10 cm ASA pipes (4 m)		(4·5/4·5) 25°			
(C) METHANE					
10 cm ASA pipes (4 m)		(–/9) 25°	—	—	—

beam to one with its axis at 25° to the beam. At this most favourable orientation with 3 cm between the flanges the EED absorbed an average power of 13 mW with a power flux density of 15 W/m^2. Using an extrapolated EED impedance, this implies that peak currents of the order of a few amperes were flowing through the device.

The above behaviour was confirmed by using the AAEE current measuring toroid. With the 15 cm ASA pipe system in its most favourable orientation and 4 cm between the flanges, at a power flux density of 4·5 W/m^2 a peak to peak current of 6 A was measured. This was the current in a 1 cm diameter bolt connected between the flanges. With this bolt insulated from the flanges and a resistor connected between the flanges, currents of 0·35 and 0·47 A pk–pk were measured in 68 Ω and 47 Ω resistors repectively. During these experiments it was noted that a person touching the outside of the pipe produced no significant effects on the current.

The effect of connecting the end of one of the pipes to the concrete pad by a vertical pipe was to decrease the current by a factor of two.

11.2 Effect of Flanges

Comparison of the results in Table 3 for the unflanged and flanged 60 cm RLSD copper breakflash reveals the effect of flanges; there is a factor of 5 increase in the threshold power flux density for ignition with the flanged system in the 220 MHz radar beam, and no ignition was obtained with flanged systems at 3 GHz. Even with hydrogen/air mixtures, no ignitions were obtained in flanged systems with the flanges less than 2 or 3 mm apart. Figure 8 shows the effect of flange separation on the ignition threshold power flux density for the RLSD steel aerial breakflash system at 220 MHz.

Measurements with the modified EED confirmed the decrease in available power with decreasing flange separation, absorbed powers in the ratio of 0·8 : 9 : 33 being found for flanged gaps of 0·7 cm : 2·5 cm : 5·1 cm.

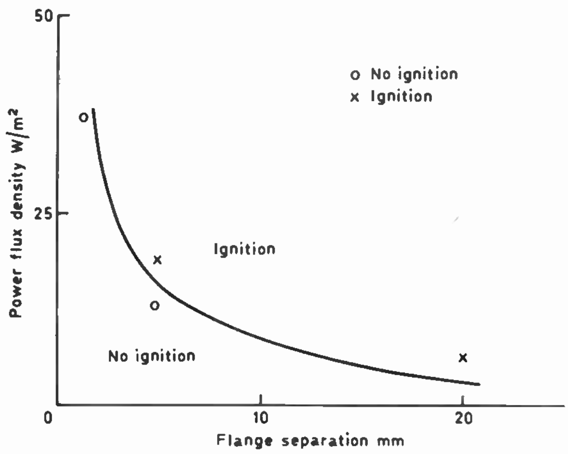


Fig. 8. Effect of flange separation on incendivity. RLSD steel 60 cm (flanged) aerial breakflash filled with hydrogen–air oriented normally to the 220 MHz beam direction.

Table 4 shows the capacitance of the aerial breakflash systems measured with an audio-frequency impedance bridge.

Table 4

Capacitance (between the two halves of dipoles) of aerial breakflash systems

(A) RLSD copper pipe dipole 2 × 30 cm + 15 cm diam. flanges

Condition	Flange or Pipe Separation	Capacitance
Flanges present	1 mm	146 pF
	5 mm	43 pF
	2 cm	21 pF
	2·5 cm	17 pF
	4 cm	10 pF
Flanges removed	4 cm	2·4 pF

No significant change when 70 cm extensions fitted.

(B) RLSD steel pipe dipole 2 × 30 cm + 22·5 cm diam. flanges

Condition	Flange or Pipe Separation	Capacitance
Flanges present	1 mm	319 pF
	5 mm	89 pF
	2 cm	35 pF
	2·5 cm	31 pF
	4 cm	16 pF
Flanges removed	2·5 cm	1·3 pF
	4 cm	1·2 pF

No significant change when 70 cm extensions fitted.

(C) ASA pipe dipoles 2 × 1·8 m, 10 and 15 cm diam.

10 cm pipe		15 cm pipe	
Flanges separation (mm)	C(pF)	Flange separation (mm)	C(pF)
64	9·1	76	11
51	10·6	42	17
35	14·2	27	23
20	21·0	10	54
12·7	31·0	6	100
7·5	51		
4·5	81		

11.3 Aerial Breakflash in Beams from Two Radar Sources

An attempt was made to determine any effects produced by irradiating the aerial breakflash simultaneously with two different radar beams, each in themselves of insufficient power to cause ignition. The transmitting radar aerials were fixed in position and therefore each pair of radar beams available intercepted at only one point. This factor, combined with the inability to vary the output of the 3, 5 and 9 GHz systems, limited the number of useful experiments which could be performed. The only method that could be used was to vary the orientation of the breakflash so that neither beam on its own caused ignition and then to irradiate the breakflash for 5 minutes with both beams simultaneously. Six tests were performed using the RLSD copper breakflash system and combining the beams at either 220 MHz and 3 GHz, or 3 and 5 GHz. No ignitions were obtained.

11.4 Sparks from the Outside of the ASA pipes

While performing the experiments with the ASA pipe systems in the 220 MHz beam, it was found that sparks could be drawn from the outside of the pipes by moving the tip of a screwdriver or other metal object along the pipe. Standing waves could be observed in this manner, the voltage nodes being between 60 cm and 80 cm apart and the flange being at an antinode. With the pipe painted, sparks could not be drawn unless the paint layer was broken. As with all the experiments reported in this paper, continuous discharges across a fixed electrode separation could not be obtained.

One experiment was carried out with the 15 cm ASA pipe at a power flux density of 1·5 W/m^2 in which an ignition of hydrogen/air was obtained with sparks produced by contacting the outside of the rusty pipe with a metal nozzle, through which the flammable mixture was flowing.

12 Discussion of Radar Results

12.1 Minimum Incendive Power Flux Densities

The use of aerial breakflash systems in the form of dipoles enables simple dipole theory to be employed to analyse the results given in Table 3.

The power, P, that can be extracted from a perfectly matched dipole is given by

$$P = \frac{S\lambda^2 G}{4\pi} \text{ watts}$$

where S is the power flux density in W/m^2

λ is the wavelength in metres and

G is the gain of the aerial.

The theoretical gain of a half-wavelength dipole is 1·5 to 1·7 and for a lossless 6-wavelength dipole it is between 2 and 4, but these values will be reduced by ohmic and ground loss resistances.

The power flux densities, S, given in Table 3 are average values, i.e. they have to be multiplied by the radar duty cycle (the inverse of the product of pulse duration, T_p and the pulse repetition rate (p.r.r.)) to calculate the corresponding peak. The extractable power during one pulse for a half-wavelength dipole is given by

$$P_p = \frac{0{\cdot}13\, S\lambda^2}{T_p \text{ p.r.r.}}$$

and the energy transferred to a matched load during a single pulse, E_p, is given by

$$E_p = P_p \times T_p$$
$$= 0{\cdot}13\, S\lambda^2/\text{p.r.r. (joules)}$$

Table 3 shows that the most sensitive breakflash is the RLSD 60 cm copper system; the overall length of 60 cm means that the breakflash is a half-wavelength long at 220 MHz and 6 wavelengths long at 3 GHz. One can analyse the results using the above formulae and, providing that no allowance is made for the possible extra gain of the 6-wavelength system, Table 5 is obtained. In calculating the figures at 3 GHz the effective power flux density is half that quoted in Table 3 because of the circular polarization. (See Sect. 10.2).

Table 5

Ignition threshold energy values for the RLSD 60 cm copper aerial breakflash, calculated from the data in Table 3, using ideal half-wavelength dipole theory

	H_2/air		C_2H_4/air	
Frequency	P_p (W)	E_p (μJ)	P_p (W)	E_p (μJ)
220 MHz	48	390	360	2900
3112 MHz	70	350	—	—

It is interesting to compare the energy values for hydrogen/air with those from other experiments. Although the minimum ignition energy for hydrogen is about 20 microjoules, when the discharge energy for ignition is determined by discharging a capacitor, using a contact system similar to that used in the r.f. experiments,[15] a value of about 100 μJ is obtained at voltage levels corresponding to the estimated open-circuit voltage (V_{oc}) in the half-wavelength dipole experiments, namely

$$V_{oc} = 2\sqrt{P_p 73}$$

which equals 118 V r.m.s. for 48 W into 73 Ω (73 Ω being the source impedance of a half-wavelength dipole). The value of E_p is nearly four times the 100 μJ value but it must be remembered that the 100 μJ figure is the actual discharge energy, whereas 390 μJ is the maximum possible value into a fixed matched load to the dipole, which a discharge most certainly is not. Taking these factors into account, therefore, the results at 220 MHz can be regarded as consistent with what would be expected from a simple theoretical approach to assessing energy transfer into a discharge from a half-wavelength dipole. The efficiency of energy transfer would have to have a value of about 25%, which does not appear unreasonable, particularly when it is considered that the contact systems used were not specially designed to be efficient at radar frequencies, but rather to represent possible practical sparking situations.

The energy value at 3112 MHz, neglecting any gain in this 6-wavelength dipole, is quite close to the 220 MHz value. The orientation of the 6-wavelength dipole is important and although attempts were made to find the optimum position, this had to be done by trial and error—the power flux density exceeded the biological safe limit and no precise angular adjustments were possible. It can only be concluded that the experiments carried out were not sufficiently sensitive to indicate whether or not the 6-wavelength dipole had a small gain over a half-wavelength dipole, because of uncertainties in orientation, loss resistance etc. Also, it has to be noted that at 3 GHz a shunt capacitance of 1 pF has an impedance of 50 Ω, so that almost certainly any gain will be offset by such shunt capacitance effects. Therefore, it appears again, as at 220 MHz, that there is agreement better than an order of magnitude between the calculated values of the maximum possible energy that can be extracted at the ignition threshold and the values predicted from other ignition experiments. That such agreement exists enables considerable confidence to be placed on the way in which these experiments were carried out.

The experiments were performed close to the aerials and, therefore, in non-uniform fields. However, as discussed in Sect. 10.2, no major interference patterns were detected. The energy correlation discussed above and the correlation between the results from the RLSD copper aerial breakflashes with the two different lengths indicates that any effects of non-uniformity did not have any significant effects on the determinations of minimum field intensity for ignition.

It is of interest to compare the results with those of Reference 13 in which minimum ignition energies were determined at the Admiralty Surface Weapons Establishment using the RLSD miniature coaxial breakflash (Fig. 7) connected directly to a 220 MHz transmitter of similar characteristics to the one at the REG. (In a perfunctory series of experiments at the REG facilities this miniature breakflash was connected across the flanges of the 10 cm ASA system as described in Sect. 10.3.2. Similar results were found to those when the flanges were bridged by the copper rod.)

The ASWE results indicated that the ignition thresholds corresponded to extractable energies of 1·6, 2·5 and 5 mJ into a matched load respectively for hydrogen/air, ethylene/air and methane/air. The ethylene results agree well with the Table 5 values. The methane results are reasonable if the ratio of 2 for ethylene/methane in the 10 cm ASA system is considered (see Table 3) but there is a discrepancy with the hydrogen results. It is pointed out in Ref. 13 that there is some doubt as to the hydrogen figure because of experimental difficulties. It can, therefore, be concluded that the general agreement with the ASWE results is reasonable.

Table 6

Power and energy ratios for incendive discharges in hydrogen, ethylene and methane for various discharge sources

Type of circuit	H_2	C_2H_2	CH_4
200V resistive (m.i.c.)	14mA	23mA	35mA
Power ratio	1·0	1·6	2·5
20V resistive (m.i.c.)	0·45A	1·2A	2·45A
Power ratio	1·0	2·7	5·4
24V 100 mH (m.i.c.)	28mA	56mA	105mA
Energy ratio	1·0	4	14·1
0·1 μF capacitive (m.i.v.)	47V		300V
Energy ratio	1·0		50·7
Minimum ignition energies	20μJ	85μJ	280μJ
Energy ratio	1·0	4·2	14·0
Aerial/breakflash systems irradiated at 220 MHz:			
Minimum incendive powers	0·4 Wm^{-2}	2·5 Wm^{-2}	
Power/energy ratio	1	6	> 12

m.i.c.—minimum igniting current
m.i.v.—minimum igniting voltage

In view of the results described in this paper, it is not surprising that the use of 12·6 mW/m^2 in Ref. 12 produced a negative result.

It is instructive to compare the ratio of ignition powers and energies for various gases from other types of circuit. This information can be derived, e.g. from BASEEFA Standard SFA: 3012: intrinsic safety.[15] Some examples are given in Table 6.

Examination of this Table shows that there are considerable variations in the power/energy ratios, depending on the circuit considered. The major difference is between the ratio of powers for continuous sources, where the power and energy are not directly connected because the energy then depends on the discharge duration, and the ratio of energy for those circuits in which the discharge energy is fixed by the circuit. The REG tests are in fact comparable to the fixed energy situation because the discharge duration is determined by the pulse width and one would, therefore, expect to see ratios between the various gases appropriate for energy-limited circuits. The minimum ignition energies relate to non-quenched conditions and the higher ratios for the 0·1 μF capacitance circuits probably approach more closely the ratios to be expected in the present experiments because they relate to a similar electrode system. The ratios for inductive circuits relate to high speed electrode separations produced in the IEC breakflash apparatus and are probably not relevant here. The ratio of 6 : 1 for ethylene compared to hydrogen obtained in these radar experiments is therefore not unexpected and the predicted ratio for methane to hydrogen is probably in excess of 20.

12.2 Orientation Effects

The results in Table 3 indicate that for a half-wavelength dipole the most favourable orientation (m.f.o.) is with its axis normal to the radar beam, for a 1½-wavelength system at 45° to the beam and for 3 and 6-wavelength systems at 25° to the beam. If these figures are compared with the maximum directivity patterns for dipoles,[17] there is excellent agreement between the m.f.o. and the position of the main directivity lobe for each type of dipole. Similar m.f.o. effects might possibly be caused by the effect of non-uniform fields. The experiments were either carried out in the near field, the Fresnel zone (3 GHz), or just outside the near field of the aerials (220 MHz) and thus some non-uniformity is expected. In one or two experiments the symmetry of the m.f.o. with respect to the radar beam was confirmed by rotating the breakflash through 180°. Therefore it is considered that the m.f.o. effects are more likely to be the result of the aerial-breakflash behaving as a theoretical dipole than the result of non-uniform fields. If the energy argument pursued in Section 12.1 is correct, this means that the 6-wavelength system did not have a high gain; this can be explained by assuming the presence of ohmic or ground losses etc. which would reduce the aerial efficiency but not significantly alter the directivity; on the other hand it may be due to poorer power transfer from the aerial to the discharge at the higher frequencies.

12.3 Flange Effects

As shown in Fig. 8, higher power flux densities were required for ignition as the distance between the pipes flanges was decreased. Table 4 shows the variation in capacitance and thus the effect can be explained by postulating that the capacitance between the flanges tends to reduce the voltage and power available.

12.4 Multiple Transmission Experiments

The period between coincident pulses with non-synchronized pulsed transmissions will depend on the difference between the pulse repetition rates (p.r.r.) and their relative actual values. The period between the coincidence of infinitely short pulses depends on the lowest common factor of the two p.r.r. It is not possible to state in the present experiments how often coincident pulses could occur without knowing the exact p.r.r. and the stability of the transmissions. However, if one assumes that coincidences occurred once a second, then the breakflash system would experience coincident pulses 300 times less frequently than it would experience pulses in the single transmission experiments. Therefore, the negative result in these superficial experiments can only be taken as an indication of the lack of addition of power, with respect to incendivity, for two pulsed radar beams. A conclusive experiment as to the lack of addition of power would require breakflash tests of long duration.

13 Conclusions from Radar Results

(1) The most sensitive aerial-breakflash was the RLSD 60 cm long copper dipole without flanges. Using this system it was found that the minimum mean power flux density required to ignite hydrogen-air mixtures was between 0·3 and 0·4 W/m² with a 220 MHz (8 μs pulse) transmission, and between 140 and 175 W/m² with a 3 GHz (5 μs pulse) transmission. In the same system it was found that the minimum mean power flux density required to ignite ethylene–air mixtures was 2·5 W/m² with a 220 MHz (8 μs pulse) transmission. To put these figures in perspective, the direct beam from a 20 dB gain aerial, transmitting 8 μs pulses, 250 times per second, at a mean transmitter power of 800 W, would have a mean power flux density of 0·4 W/m² at a distance of approximately 130 metres from the aerial.

It was not found possible, with any of the breakflash systems used, to ignite hydrogen–air mixtures with either, a 5 GHz (5 μs pulse) transmission with mean power flux densities of up to 350 W/m² or, with a 9 GHz continuous wave transmission with power flux densities of up to 600 W/m². Nor was it found possible to ignite ethylene–air mixtures with a 3 GHz (5 μs pulse) transmission with mean power flux densities of up to 500 W/m².

(2) The minimum incendive power flux density of long dipoles is very sensitive to the orientation of the receiving structure—the values found for the most favourable orientation are explicable in terms of dipole antenna theory.

(3) The effect of flanges on the pipes at the centre of a dipole system is to increase the power flux density required for the production of an incendive spark in a breakflash apparatus connected between the flanges.

(4) In the experiments to determine the effect of multiple transmissions, these experiments being limited in number and duration, no ignitions were obtained when aerial breakflashes were subject to two simultaneous transmissions, each one of which was just below the corresponding power flux density necessary to produce an ignition in a single transmission test.

Part 3 IGNITION THRESHOLDS FOR MULTI-FREQUENCY R.F. SOURCES

D. J. Burstow and D. W. Widginton

All of the available information on experimental ignition threshold data previously available relates to a situation in which only a single frequency source is present. The question arises whether, in practical situations, significant contributions of energy from a number of different sources could give rise to gas ignitions. In practice, assessments of ignition threshold values have to be made when more than one frequency is present. It will be shown that in the majority of cases significant power can only be extracted from a structure when it is near resonance and that when more than one frequency is present it is unlikely that off-resonant frequencies can contribute significantly, unless the frequency differences are small, or the structure exhibits resonances at a number of frequencies which coincide with the frequencies of the incident transmissions.

For single frequency sources, attention has been focused on the available power which may be delivered into an optimum resistive load as the parameter which characterizes incendivity. It is, however, more usual to use energy as a characteristic parameter for spark ignition. However, this can only be done directly when the energy of discharges from a given source can be specified, as for example, in a d.c. inductive circuit. Considerable evidence is now to hand that if the power available from a source is integrated over a characteristic integration time for the specific flammable gas/air mixture in question, then a value of energy is obtained which characterizes the ignition threshold. The characteristic integration times for various gases have been measured experimentally in a number of ways, and have also been predicted theoretically.[18] The values for this integration time are about 20 μs for hydrogen/air, and about 100 μs for ethylene and propane gas/air mixtures.

14 Simple Resistive Sources

Consider first a simple circuit in which a resistive r.f. source, having a source resistance R, is driven at two frequencies, so that individually each frequency produces equal voltages, V, across and powers, P, in a matched load R. It is well known that beats are produced in such a circuit and the mean power dissipated in R is $2P$, with peaks of $4P$ because of the beat effects. The question then arises whether it is the mean or peak power which characterizes incendivity, or indeed whether some other parameter is more appropriate.

It is postulated in this paper that the maximum energy available from the source during the period of time, t_c, the integration time, provides a realistic basis for estimating the effect of the beats. It is clear, however, that in doing this, the energy dissipated in the matched load depends, not only on t_c, but also on the phasing of the two waveforms and the time (point on wave) chosen to start the integration period. Conditions have to be such that the choice of starting time leads to the maximum possible value of energy dissipated in order to be able to say that the energy available within a period of t_c will always be less than the threshold value for ignition.

15 More Complex Sources

The simple resistive source model is one in which the optimum load resistance for both power and energy transfer is fixed and independent of frequency. In most practical situations this will not be the case, and different values of optimum load resistance will apply at the different frequencies involved. We can, however, consider the energy which is dissipated in a fixed value of resistance R since this assumption does not lead to an underestimation of the possible hazard.

The analysis of maximum available energy into a resistive load can be made on the basis that this load will have a fixed value, chosen so that it is the optimum value for the particular source and actual frequencies concerned. The energy of any continuous discharge is then automatically limited to a value less than that available for this optimum value of resistance.

The contribution of the ith source ($i = 1, 2 \ldots n$) of frequency f_i to the voltage across the resistive load R is $V_i \cos \omega_i t$ ($\omega_i = 2\pi f_i$, and all voltages are assumed to be in phase at $t = 0$ with no loss of generality), so that the combined voltage is given by

$$\sum_{i=1}^{n} V_i \cos \omega_i t.$$

The energy dissipated in the load R during a time interval δT, starting at time T, is then given by

$$E(T, \delta T) = \frac{1}{R} \int_{T}^{T+\delta T} \left\{ \sum_{i=1}^{n} V_i \cos \omega_i t \right\}^2 \mathrm{d}t$$

Since $20\,\mu\text{s} < \delta T < 200\,\mu\text{s}$ and provided that

$$\omega_i,\ \omega_{i+j} \gg \omega_i - \omega_j \text{ and } 1/\omega_i \ll T,$$

as will generally be the case, it can be shown that to a good approximation:

$$E(T, \delta T) = \sum_{i=1}^{n} \frac{V_i^2\, \delta T}{2R} +$$

$$+ \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \frac{2V_i V_j}{R} \frac{\sin(\omega_i - \omega_j)\dfrac{\delta T}{2} \cos(\omega_i - \omega_j)\left(T + \dfrac{\delta T}{2}\right)}{\omega_i - \omega_j}$$

and hence

$$E(T, \delta T) \leqslant \sum_{i=1}^{n} \frac{V_i^2\, \delta T}{2R} + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \frac{V_i V_j\, \delta T}{R} \left| \frac{\sin x_{ij}}{x_{ij}} \right|$$

where $x_{ij} = \pi(f_i - f_j)\, \delta T$.

Since the power P_i contributed by the ith source above is given by $P_i = V_i^2/2R$ then

$$E(T, \delta T) \leqslant \delta T \left\{ \sum_{i=1}^{n} P_i + 2 \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \sqrt{P_i P_j} \left| \frac{\sin x_{ij}}{x_{ij}} \right| \right\}$$

The analysis indicates that if all values of $(f_i - f_j)$ are greater than $2/\delta T$ the threshold energy is, to a good approximation, equal to the product of integration time and the sum of the powers available for each individual source. For $\delta T = 20\,\mu$s (H_2/air) this means frequency differences greater than 100 kHz, and for $\delta T = 100\,\mu$s (ethylene, propane) frequency differences greater than

20 kHz, should be treated by summing the individual powers. Even when $(f_i - f_j)$ values lie between $1/\delta T$ and $2/\delta T$ (i.e. 50–100 kHz or 10–20 kHz respectively), the power for two sources increases only from $2P$ to $2{\cdot}44P$ at the worst, a difference hardly detectable in laboratory incendivity experiments since it corresponds to only a factor of 1·1 in terms of voltage. However, the effects produced for values of $(f_i - f_j)$ less than $1/\delta T$ should be detectable in such experiments, especially when the frequency difference becomes very small.

If P_{th} is the ignition threshold power for a single source, i.e. $E(T, \delta T) = P_{th}\, \delta T$, then for $n = 2$ and $P_1 = P_2$

$$P_1 = P_2 = P_{th}/2 \qquad \text{for } (f_1 - f_2) > 1/\delta T$$

and

$$P_1 = P_2 = P_{th}/4 \qquad \text{for } (f_1 - f_2) \rightarrow 0$$

Experiments in hydrogen and ethylene using two signal generators driving a broadband 50 Ω source produced results consistent with these predictions. For example, in hydrogen P_{th} was 6·25 W for a single 2 MHz source. With frequency differences greater than 50 kHz each source contributed 2·85 W at the ignition threshold, so that $P_1 = P_2 = P_{th}/1{\cdot}82$. With frequencies of 2 MHz and 2·01 MHz each source contributed 1·56 W, and $P_1 = P_2 = P_{th}/4$. In ethylene, frequency differences greater than 10 kHz gave $P_1 = P_2 = P_{th}/1{\cdot}8$. Smaller frequency differences could not be obtained because of pulling between the signal generators.

16 Pulsed Sources

The situation considered above is for continuous wave sources of differing frequency. If several pulsed radar transmissions are present, it can be shown that it is necessary to take account of the simultaneous irradiation of a structure by all the radar beams, although such coincidences will be present for only a small proportion of the time.

For conventional pulsed radars the pulse widths are less than the integration time t_c of 20 or 100 μs, and in practice, the possibility that frequency differences between different radars will be sufficiently small to give rise to beat effects can be disregarded. It therefore follows that the energy extractable during any period t_c is obtained simply by adding the energies extractable from each pulse occurring during that period. Again, the pulse repetition rate of conventional radars is much less than $1/t_c$, so that the addition involves only pulses from different radar beams and the maximum extractable energy can be expressed as

$$E_{max} = \sum_{i=1}^{n} P_i T_i$$

where P_i is the maximum extractable pulse power for the ith radar beam which has a pulse duration of T_i.

Appropriate ignition threshold values for E_{max} can be derived from the work reported in Part 2, i.e. 390 μJ for hydrogen–air mixtures and 2900 μJ for ethylene–air mixtures.

17 Conclusions on Multi-frequency Effects

(1) It has been shown theoretically and confirmed by experiment that it is possible to calculate the ignition threshold values for multi-frequency continuous wave situations on the basis of a constant value of ignition threshold energy. This energy value is obtained by integrating the power available to an optimum resistive load over a time t_c which is specific for the particular gas/air mixture concerned. ($t_c = 20$ μs for hydrogen/air mixtures, and 100 μs for ethylene and Group IIA gas/air mixtures.)

In practical terms, if powers P_i $(i = 1, 2, \ldots n)$ are available from a source at a frequency f_i, in order to assess the combined effect, the power can be calculated from

$$P = \sum_{i=1}^{n} P_i + 2 \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \sqrt{P_i P_j}\, \frac{|\sin x_{ij}|}{x_{ij}}$$

where $x_{ij} = \pi\,(f_i - f_j)\, t_c$

P can then be compared with the ignition threshold values of power for r.f. ignition, i.e. 2 W for H_2/air, 7 W for ethylene/air and 10 W for methane/air, in order to assess whether or not ignition is possible. Provided that all

$$x_{ij} > 2\pi, \text{ i.e. } (f_i - f_j) > 2/t_c,$$

then it is sufficient to take

$$P = \sum_{i=1}^{n} P_i$$

(2) In the case of pulse transmissions, it is the sum of the energies extractable from each individual pulse incident on the structure within the integration time t_c for the flammable gas which is relevant to the ignition hazard, so that

$$E_{max} = \sum_{i=1}^{n} P_i T_i$$

provided that the pulse repetition rate is much less than $1/t_c$.

18 Acknowledgments

The authors gratefully acknowledge the contribution from Dr Tromans and other officers of Shell Research to the radar experiments and offer their thanks to the officers of the Royal Ordnance Branch and personnel of AAEE for making the radar tests possible and the officers of the Admiralty Surface Weapons Establishment for many helpful discussions.

19 References

1 Report of a Working Group on Radio Ignition Hazards at St Fergus, Scotland. Health and Safety Executive, July 1978.
2 Report of the Steering Committee on Radio Frequency Ignition Hazards at St Fergus, Scotland. Health and Safety Executive, March 1979.
3 Draft Revision of BS 4992: 1976. BSI Document 76/27631.
4 Bittner, G., 'Ignition of explosive atmospheres by sparks in the frequency range of 1 kHz to 10 MHz', *PTB Mitteilungen*, **86**, no. 1. pp. 26–30, 1976.
5 Howson, D. P. and Butcher, G., 'A coaxial breakflash for r.f. ignition of flammable vapours', *Proc. Instn Elect. Engrs*, **122**, pp. 1453–4, December 1975.
6 Howson, D. P., Butcher, G. H. and Excell, P. S. 'Ignition of various gas/air mixtures by sparks from 2 MHz or 9 MHz sources', *The Radio and Electronic Engineer*, **51**, no. 4, pp. 170–4, April 1981.
7 Gehm, K. H., 'The ignition of explosive mixtures by high frequency energy' Gottwaldov Conference, Czechoslovakia, 1968. (Available as SMRE Translation No. 5830).
8 Glazier, E. V. D. and Lamont, H. R. L., 'Services' Textbook of Radio', Vol. 5, Transmission and Propagation (HMSO, London, 1958).
9 British Standard BS 5501: Part 7: 1977 'Electrical apparatus for potentially explosive atmospheres. Part 7 Intrinsic Safety (i). (British Standards Institution, London, 1977).
10 Tomlinson, R. and Widginton, D. W., 'An analogue/digital storage system for intrinsic safety research' HSE Technical Paper No. 3, 1978.
11 Ghobrial, S. I. *et al.* 'Hazards to inflammable fuels and vapours due to induced microwave radiation', *The Radio and Electronic Engineer*, **45**, no. 2, pp. 64–8, February 1978.
12 Lester, D., 'Determination of the minimum electromagnetic field intensity required to ignite a hydrogen/air gaseous mixture' Report TR-740, Telemetric Systems Division, NASA, Kennedy Space Centre.
13 Rosenfeld, J. L. J. *et al.*, 'Incendivity of discharges in breakflashes directly connected to a 220 MHz transmitter', Shell Research, (To be published).
14 Narda Electromagnetic Radiation Monitors, Aveley Electric, Chessington, Surrey, England.
15 BASEEFA Standard SFA: 3012 'Intrinsic Safety', BASEEFA, Buxton, England.
16 Lewis, B. and Van Elbe, G., 'Combustion, Flame and Explosions of Gases', 2nd Edition (Academic Press, New York, 1961).
17 Excell, P. and Hanson, P. G., 'Performance of long dipoles as unintended receiving antennas', Conference on Electromagnetic Compatibility, Guildford, April 1978, IERE Conference Proceedings No. 39.
18 Rosenfeld, J., Strachan, D. and Tromans, P. S. 'Experiments on the incendivity of r.f. breakflash discharges (1·8 to 21 MHz continuous wave)', *The Radio and Electronic Engineer*, **51**, no. 4, pp. 175–86, April 1981.

Manuscript first received by the Institution on 7th July 1980 and in final form on 15th December 1980.
(Paper No. 1978/Comm 215)

The Authors

David Burstow is one of HM Senior Electrical Inspectors of Factories and has previously had special responsibilities in the field of r.f. ignition hazards. His present work is of a more general nature and he is based at Manchester as a consultant electrical inspector. He graduated at Bristol University in 1965 and worked with the East Midlands Electricity Board before joining the Factory Inspectorate in 1976. He played a major role in the investigation of the r.f. ignition hazards particularly at the St Fergus and Mossmorran gas processing sites.

Ronald Loveland is one of HM Senior Electrical Inspectors of Factories with special responsibilities in the fields of r.f. ignition hazards, electrostatic ignition hazards and the use of explosion-protected electrical equipment. He graduated in physics at Leicester University in 1967 and worked in EMI Research before obtaining a Ph.D. at Dundee University in 1971. He joined the Electrical Research Association in 1974 and moved to HM Factory Inspectorate in 1976. Dr Loveland has been closely involved with the Health and Safety Executive investigations into the potential r.f. ignition hazards at various sites, including the major natural gas processing plants at St Fergus and Mossmorran in Scotland, and he is at present participating in the production of a revised British Standard on this subject.

Richard Tomlinson is a Senior Scientific Officer with the Research and Laboratory Services Division of the Health and Safety Executive. He gained a Higher National Certificate in electrical engineering in 1959 and initially spent some 15 years in the intrinsic safety field, testing light duty electrical equipment intended for use in flammable atmospheres. Since 1969 he has worked in the Electrical Hazards Section carrying out research into many aspects of spark ignition.

David Widginton obtained his degree in mathematical statistics at University College London in 1951 and in 1953 joined the Safety in Mines Research Establishment which is now part of the Research and Laboratory Services Division of the Health and Safety Executive. He is currently head of the Electrical Hazards Section and has been involved since 1958 with research into the safe use of electrical equipment in hazardous atmospheres, especially the prevention of spark ignition hazards. He is Chairman of BSI Sub-committee GEL/114/2 Intrinsically Safe Apparatus.

UDC 621.3–768.3: 621.3.029.53
Indexing Terms: Spark discharges, r.f., Gases, ignition, R.f. hazards, Electromagnetic compatibility

Ignition of flammable gas/air mixtures by sparks from 2 MHz and 9 MHz sources

Professor D. P. HOWSON,
B.Sc., M.Sc., D.Sc., C.Eng., F.I.E.E., F.I.E.R.E.*

P. S. EXCELL,
B.Sc., Ph.D., M.I.E.E.E., C.Eng., M.I.E.E.*

and

G. H. BUTCHER, M.Sc.*

SUMMARY

Measurements have been made of the voltages and powers required for the radio frequency (r.f.) spark ignition of various gas/air mixtures. The spark-ignition chambers (s.i.c.) used were make-and-break mechanisms, hereafter called 'breakflashes', employing tungsten wires scraping over a grooved cadmium disk or rod. The breakflashes were connected to the r.f. sources by means of a resistive L-type attenuator which damped any overshoots in the output voltage and resulted in a resistive 50 Ω source impedance being seen by the breakflash.

Measurements were also made with a quarter-wavelength long antenna between the r.f. source and the breakflash cell. The high impedance seen by the breakflash resulted in ignition at available power levels significantly lower than with the directly-connected sources.

* *Postgraduate School of Electrical and Electronic Engineering, University of Bradford, Bradford, West Yorkshire, BD7 1DP*

The Radio and Electronic Engineer, Vol. 51, No. 4, pp. 170–174, April 1981

1 Introduction

Previous workers[1,2] have reported widely-differing values of open circuit voltage and powers necessary for the ignition of optimum gas/air mixtures at medium and high frequencies. Furthermore, a recent experiment by the Admiralty Surface Weapons Establishment (unpublished) has shown that ignitions in hydrocarbon/air mixtures may be obtained in certain circumstances with considerably less power than the original tests had predicted. The series of tests reported here were undertaken primarily to obtain comparative data for various gas/air mixtures at two frequencies most relevant to the recent investigations of potential radiofrequency ignition hazards at the St Fergus natural gas terminal,[3] and also to throw some light on the discrepancies mentioned above, attempting to clarify the most appropriate criteria that might be adopted for the purposes of a hazard assessment.

Two series of experiments have been undertaken. In Section 2, experiments are described with a breakflash in a circuit configuration having a quarter-wavelength wire loop interposed between the r.f. source and the breakflash. Section 3 describes the results from experiments in which a direct connection was used between the amplifier and the breakflash (except for a resistive pad), which resulted in a resistive 50 Ω source being presented to the breakflash.

In all cases the breakflashes used a grooved disk or cylinder made of cadmium (except for one test using rusted steel—see Sect. 3.2) as one spark electrode, and a tungsten wire (or wires) as the other.

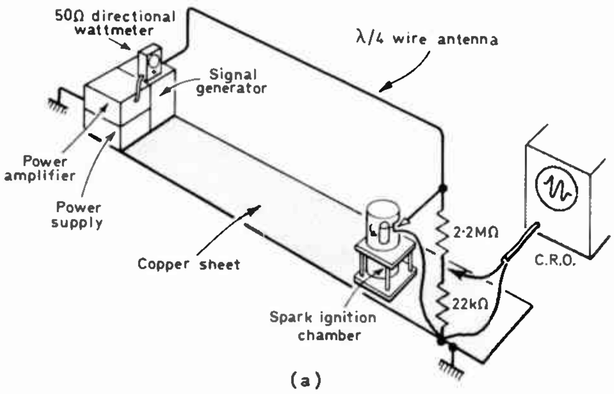
2 Tests with a High Impedance Source

In these experiments the power source was a Redifon solid-state power amplifier with a (nominally) 50 Ω output impedance driven from a Redifon signal generator. A quarter-wavelength long thin wire (analogous to a loop antenna) was connected to the output of the power amplifier, and a spark ignition chamber (s.i.c.) in the form of a breakflash was attached to the remote end of the wire. The length of the wire was adjusted with the breakflash open-circuit until the quarter-wavelength resonance was achieved. Fine tuning was achieved by adjusting the frequency slightly: the experimental layout is shown in Figure 1(a) for the 9·1 MHz system.

Breakflashes of two designs were used as spark ignition chambers: a novel design developed at Bradford University (Fig. 1(b)) and a standard IEC breakflash,[4] modified to reduce the electrode capacitance.[5] The IEC breakflash has been found to be the most sensitive in wide international experience over many years in d.c., 50 Hz and r.f. circuits. The new Bradford design was evolved in an attempt to exploit the principle of the IEC version in a structure more suited to use over a wide range of radio frequencies and source impedances.

Using an optimum hydrogen/air mixture, the

0033–7722/81/040170+05 $1.50/0



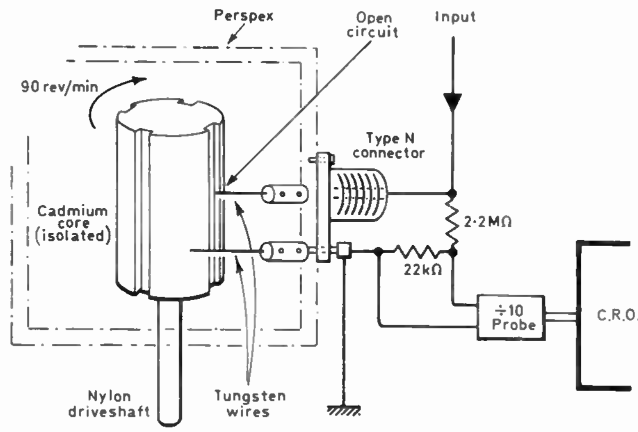


Fig. 1. (a) 9·1 MHz resonant antenna.
(b) Spark ignition chamber (Breakflash) (Bradford University).

(b)

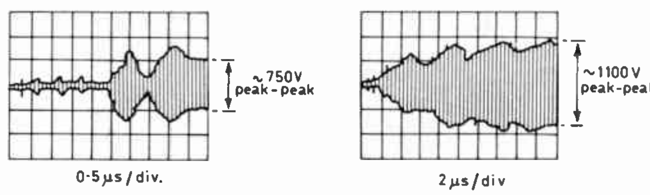
Bradford University breakflash performed as efficiently as the IEC breakflash[4] in the standard 24 V d.c. calibration tests for breakflashes. However, differences in r.f. behaviour were observed and these are discussed in Section 3.1.

The high output impedance of the quarter-wavelength line necessitated a potential divider circuit for measurements. This was calibrated *in situ* at the appropriate frequencies to reduce possible measurement errors.

Initial tests with the system concentrated on finding the most easily ignited gas/air mixture for methane and hydrogen at n.t.p. with a 9·1 MHz signal. The figures obtained were the same, within experimental error, as previous workers have found in d.c. tests, i.e. 8·3% by volume for methane/air and 20·2% by volume for hydrogen/air.

The 9·1 MHz signal was then used to determine the minimum open circuit voltage and available spark power required for the ignition of optimum gas mixtures. Figures 2(a) and (b) give the probability of ignition for the two mixtures as a function of the available power, determined as follows: Using a 'Thruline' wattmeter after the power amplifier, it was observed that the reverse power was low, indicating that the antenna system with the breakflash open circuit had an input impedance of approximately 50 Ω. A vector impedance meter measurement of the output impedance of the line at resonance has a value of 2·0 kΩ (resistive) at 9·1 MHz. This, with the open circuit voltage, was then used to calculate the maximum available power for the breakflash, assuming that it must present (transiently) a matched load to the source resistance (Power = $\hat{V}_{oc}^2/8R_{source}$).

The open circuit voltage at 0·1% probability of ignition of a methane/air mixture was 440 V peak, and in a hydrogen/air mixture 290 V peak.



(a) hydrogen/air at 8·4 W (b) methane/air at 20 W.

Fig. 3. Breakspark voltage waveforms (λ/4 tuned line)

Typical breakspark waveforms for hydrogen/air and methane/air are illustrated in Fig. 3. A study of these suggests that the first part of the discharge is the result of arcing at approximately 10 V in the metal vapour, giving a nearly complete mismatch to the transmitter, and therefore a power of only 1 W or so is available in this initial period, say 2·5 μs. With this form of spark, it appears that most energy is dissipated in the following

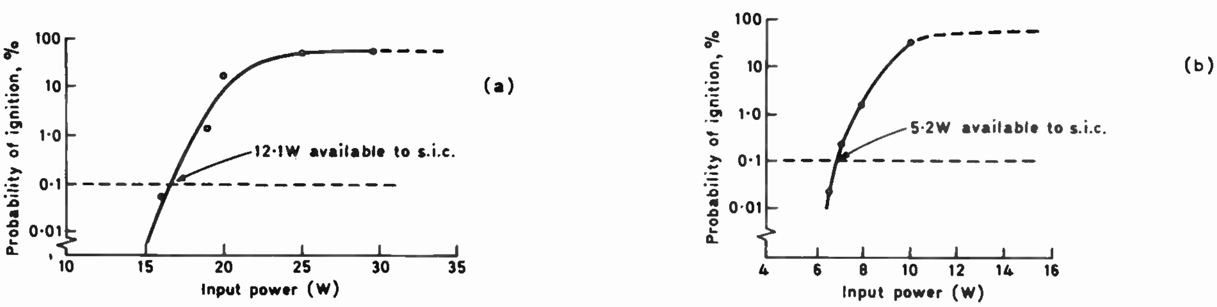


Fig. 2. Probability of ignition for (a) methane/air mixture and (b) hydrogen/air mixture at 9·1 MHz (λ/4 tuned line) (s.i.c. = spark ignition chamber) (The difference between the power input to the system and that available to the s.i.c. is due to losses in the λ/4 line).

disturbed high voltage discharge. The second part of the discharge has a duration of approximately 2 µs in hydrogen and 16 µs in methane. This indicates discharge energies of approximately 15 µJ and 300 µJ respectively. These figures are close to the accepted minimum ignition energies for the two gases, although the ratio of powers needed for ignition of 8 and 20 W is very different.

Similar tests were made with the 2·16 MHz system. Figures 4(a) to (e) give the probability of ignition for various optimum gas/air mixtures as a function of available source power. The vector impedance meter was used to measure the output impedance of the tuned loop and this was 2·1 kΩ at 2·16 MHz. The open circuit voltage for 0·1% probability of ignition ranged from

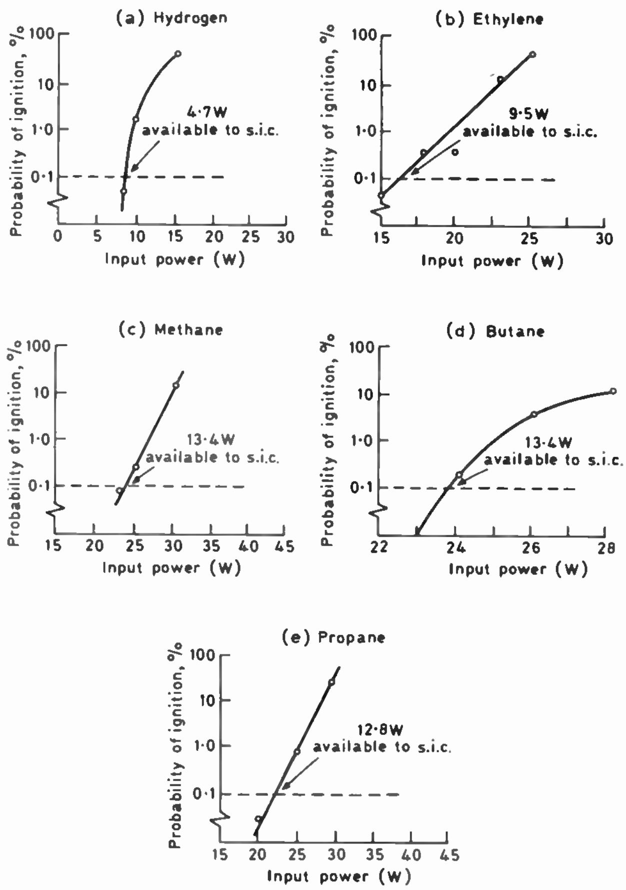


Fig. 4. Probability of ignition at 2·16 MHz (λ/4 resonant line) (s.i.c. = spark ignition chamber).

284 V peak for hydrogen/air to 480 V peak for methane/air and butane/air. This means that the available power at the breakflash ranged from 4·7 W for hydrogen/air to 13·4 W for methane/air and butane/air, similar to the figures noted at 9·1 MHz in Fig. 2.

3 Tests with a 50-ohm Resistive Source

Initial tests were performed with a Marconi NT203 broadband valve amplifier. Tests on this amplifier established that at output power levels of 100 to 200 W and a frequency of 2 MHz the output impedance was

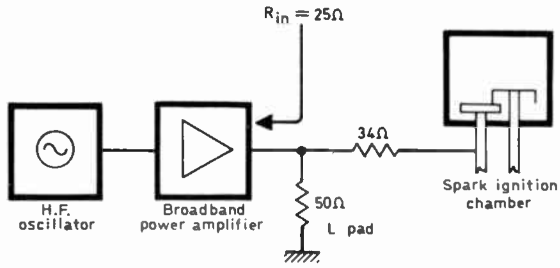


Fig. 5. 50 Ω ignition system for 2 MHz.

approximately 25 Ω and not completely resistive. Accordingly, in the main tests an L-type pad of resistances was placed between the amplifier and the test cell, as shown in Fig. 5.

3.1 Variation of Circuit and Breakflash Configurations

A preliminary series of tests was undertaken without the use of the L pad in order to assess the differences, if any, between the sensitivity of the earliest test configurations.[1,2] In the previous Bradford tests, a λ/8 50 Ω coaxial line was used between the breakflash and the power amplifier, so that the impedance presented to the amplifier did not vary much in magnitude. Additionally, a different breakflash in the form of a coaxial cell was used,[1] similar to that shown in Fig. 1(b) in that the tungsten wires also crossed the grooved cadmium rod at right-angles but having a constant 50 Ω characteristic impedance.

Four tests were undertaken:

1. With a λ/8 line and the Bradford University breakflash and a 500 Ω damping resistor across the breakflash.
2. With a direct connection to the Bradford University breakflash and a 500 Ω damping resistor across the breakflash.
3. Ditto, but without the damping resistor.
4. With a direct connection to a modified IEC breakflash,[4] without a damping resistor.

For ignition of an optimum hydrogen/air mixture, the following results were obtained at the 0·01% probability level, this level being chosen to allow comparison with the work of Bittner.[2]

Table 1 shows quite clearly that the modified IEC breakflash is considerably more sensitive than the more recent Bradford University breakflash at 2 MHz—this is probably because, occasionally, long duration and therefore high energy sparks are produced in the former. (Further tests have shown little difference in sensitivity of the cells for hydrocarbon/air mixtures.) Additionally, the results show that the inclusion of the 1/8th wavelength line has a further desensitizing effect. In contrast, the inclusion of the damping resistance has a relatively small effect. The result of Bittner,[2] taken with a 50 Ω source impedance corresponding to the situation in (iv) is 60 V and 9 W.

3.2 Tests with the Modified IEC Breakflash

The main series of tests were undertaken with the aforementioned L pad between the amplifier and the modified IEC breakflash in order to damp the overshoots noticed in the voltage waveforms observed during ignitions in the preliminary series of tests. With the pad in use, switching overshoots were limited to a maximum of 10%.

The results obtained at the 0·01% probability level of ignition in optimum gas/air mixtures are shown in Table 2. The results generally confirm those of Bittner, which were performed with a similar cell and a similar test circuit. The probability values are shown in more detail in Figs 6(a) to (e). The exception to the above is the result for hydrogen, which is considerably higher than the Bittner result. The hydrogen result appears to be particularly sensitive to the form of the electrode surfaces in the cell—early results with smooth surfaces on the grooved cadmium disk did not produce ignitions for peak open-circuit voltages of less than 190 V. The smoothing effect of the tungsten wires rubbing on the cadmium surface ensured that this was the lowest figure that could be obtained in systematic tests at a series of power levels (see Fig. 6(a)). With a freshly sanded cadmium disk it was possible to obtain an ignition of hydrogen/air at an early stage in a test with a peak open-circuit voltage of only 100 V, no further ignitions being possible unless the disk was sanded again. It is impossible to associate a probability of ignition with this phenomenon (which may be due to microscopic protrusions in the cadmium surface) but it is considered to be statistically significant in the hazards-assessment context and hence this value is used in Table 2, rather than that from Fig. 6(a). It is possible that the ignition parameters are particularly sensitive to any form of stored energy in the source and that in our tests we had slightly more resistive damping than has been reported in the previous experiments.

The hydrocarbon results do, however, show a close correspondence to those of Bittner. The results for methane, butane and propane are closely similar, as would be predicted from the ratio of their minimum ignition energies. The result for ethylene is higher than would be predicted from the ratio of minimum ignition energies with methane etc., but this effect has been confirmed by Bittner; presumably in ethylene the second phase of the discharge occurs for significantly less time than in methane.

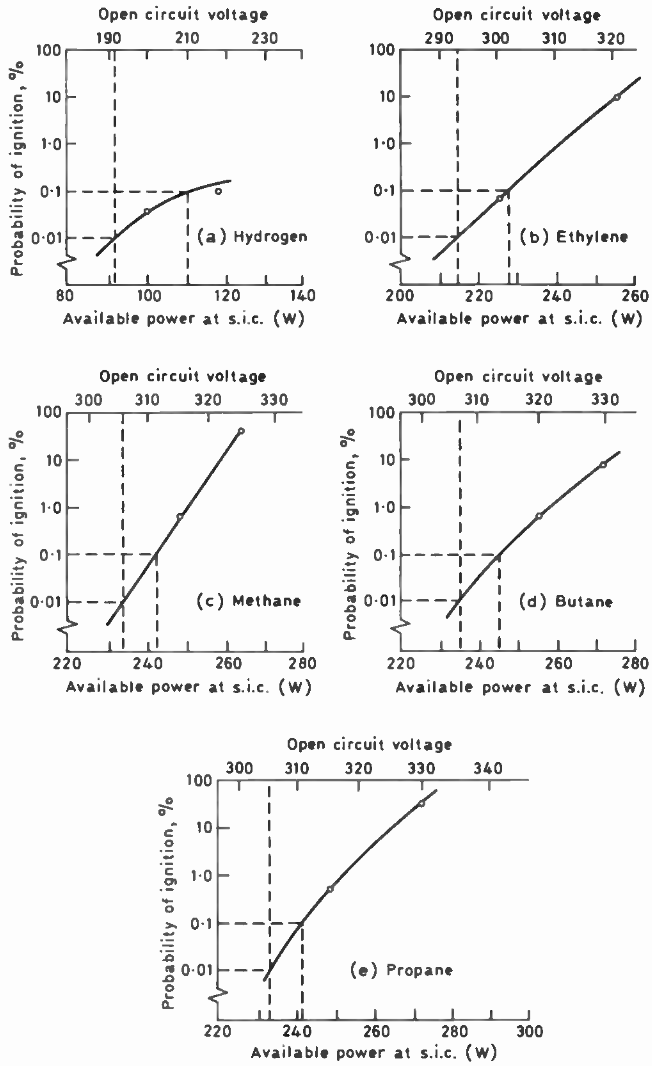


Fig. 6. Probability of ignition at 2·16 MHz (50 Ω source).

Table 1

Ignition parameters for a hydrogen/air mixture with a resistive source attached to various breakflashes with various circuit configurations (frequency: 2 MHz)

		Peak open-circuit voltage (V)	Available power (W) for spark (25 Ω source)
(i)	1/8th wavelength line plus damping resistor and Bradford breakflash (see Fig. 1(b))	130	85
(ii)	Damping resistor and Bradford breakflash	100	50
(iii)	Bradford breakflash	95	45
(iv)	Modified IEC breakflash	67	22·6

Table 2 includes results of a series of tests undertaken at 9 MHz using a Racal solid-state amplifier damped with 50 Ω in parallel with the transmitter output, together with a 25 Ω series resistance between this output and the breakflash in order to present a 50 Ω output impedance to the modified IEC breakflash. The results are generally similar to the 2 MHz figures with the exception of the ethylene results. No reason for this ethylene discrepancy has yet been found.

One further test was undertaken at 9 MHz. The cadmium disk in the breakflash was replaced with a similar disk made from deeply pitted rusty iron. For an optimum methane/air mixture there was a considerable reduction in the power required for ignition, as was reported by Widginton.[6] The figures for a 0·01% probability of ignition were 180 V peak open-circuit voltage and an average power of 80 W.

4 Conclusions

The results from this work have established reasons for the discrepancy between the previously reported Bradford University and Bittner results for the r.f. ignition of flammable gases and vapours with 50 Ω resistive sources.

The results indicate that a peak open-circuit voltage of about 300 V is necessary from a 50 Ω source for 0·01% probability of ignition of the hydrocarbons, methane, butane and propane. The corresponding figure for ethylene has been as low as 158 V.

No ignitions of hydrogen/air mixture were observed for voltages less than 100 V peak with a well-damped source.

In all cases the critical voltages at 9 MHz were found to be slightly smaller than those at 2 MHz.

The high impedance test involving a quarter-wavelength wire loop (antenna) between the r.f. source and the breakflash has shown that ignitions (0·1% probability level) occur at rather higher peak open-circuit voltages of about 400 V for hydrocarbons at both 2 MHz and 9 MHz. The corresponding figure for hydrogen/air mixtures was 285 V. When converted to power values, these are significantly lower than those in the 50 Ω resistive experiments and confirm the earlier work of ASWE (see Sect. 1).

Experiments with both types of sources have shown that the extrapolation of the ratios between the open circuit voltages or powers for different gas/air mixtures on the basis of the ratios of minimum ignition energies, although plausible, is not valid. This appears to be due to the differing nature and duration of the discharges, which are significantly longer in the hydrocarbons than they are in hydrogen.

The single test undertaken with a rusty iron electrode in a breakflash confirmed Widginton's observations[6] that ignition is possible in a methane/air mixture for voltages well below 300 V—in this case at 180 V peak at 9 MHz: the explanation for this phenomenon is not known.

5 References

1 Howson, D. P. and Butcher, G. H., 'A coaxial breakflash for r.f. ignition of flammable vapours', *Proc. Instn Elect. Engrs*, **122**, pp. 1453–4, December 1975.

2 Bittner, G., 'Über die Funkenzündung explosibler Atmosphäre im Frequenzbereich 1 kHz bis 10 MHz', *PTB-Mitteilungen*, **86**, no. 1, pp. 26–30, 1976.

3 Report of the Steering Committee on Radio Frequency Ignition Hazards at St Fergus, Scotland, Health and Safety Executive, London. 1979.

4 'Electrical Apparatus for Explosive Gas Atmospheres Pt. 3—Spark-test apparatus for intrinsically-safe circuits', International Electrotechnical Commission Publ. 79–2, 2nd Ed. 1972.

5 Butcher, G. H., 'The Effects of Frequency on the Incendivities of AC Sparks in the Range 0 to 2·5 GHz', M.Sc. Thesis, Bradford University, 1979.

6 Widginton, D., 'Ignition of flammable gases by discharges produced from structures irradiated by RF fields', Research and Laboratory Services Division, Health and Safety Executive, report to be published.

Manuscript first received by the Institution on 21st January 1980 and in final form on 20th January 1981.
(Paper No. 1981/Comm 216)

Table 2

Ignition parameters for the most sensitive spark ignition chamber, a modified IEC breakflash, connected to a resistive 50 Ω source (0·01% probability of ignition)

Gas/air mixtures	Peak open-circuit voltage (V) (Bradford)	Available power (W) (Bradford)	Peak open-circuit voltage (V) (Bittner)
(i) 2 MHz			
Hydrogen	100†	25†	60
Ethylene	293	214	260
Methane	306	233	300
Butane	307	235	
Propane	305	232	300
(ii) 9 MHz			
Hydrogen	102	26	62
Ethylene	158	62	280
Methane	230	130	300
Butane	230	130	
Propane	215	116	310
Ethane	220	120	

† See Section 3.2.

UDC 621.3-768.3: 621.3.029.53
Indexing Terms: Spark discharges, r.f., Gases, ignition, R.f. hazards
Electromagnetic compatibility

Experiments on the incendivity of radio-frequency, breakflash discharges (1·8–21 MHz c.w.)

J. L. J. ROSENFELD, B.A., Ph.D.,*
D. C. STRACHAN, B.Eng., Ph.D.,*
P. S. TROMANS, M.A., Ph.D.*
and
P. A. SEARSON, B.Sc.†

SUMMARY

The incendive properties of radio-frequency, breakflash discharges have been investigated experimentally in the 1·8–21 MHz frequency range, using a continuous wave source. Minimum powers and voltages for ignition have been measured. For ethylene/air and methane/air mixtures, matched load powers of 7 W and 12 W, respectively, must be exceeded for ignition. However, the precise form of the impedance of the radio-frequency source has an important effect, and for some sources much higher powers are required to produce an incendive discharge. The electrode material is also significant: a minimum voltage of about 300 V (peak) is required between clean metal electrodes to produce an incendive discharge, but no voltage criterion has been detected with rusty steel electrodes. The shape of the electrode is important: some shapes promote flame quenching. Neither the rate of separation of the electrodes nor the excitation frequency were found to have a significant effect on ignition. Many of the combustion aspects of the problem can be explained by a simple ignition model.

* *Shell Research Ltd., Thornton Research Centre, P.O. Box 1, Chester CH1 3SH.*
† *Loughborough University of Technology.*

The Radio and Electronic Engineer, Vol. 51, No. 4, pp. 175–186, April 1981

List of Symbols

C	capacitance
C_p	specific heat of gas
d	appropriate length scale for ignition kernel
E	activation energy of chemical reaction
h	constant
I_s	peak short-circuit current through electrodes
L	inductance
P	power dissipated in a matched load
P_i	power dissipated in gas
Q	quality factor of a resonant circuit
R	resistance, gas constant
S	laminar flame speed
t	time
t_i	time scale of ignition process
T	gas temperature
u	gas velocity
V_0	peak open-circuit voltage between electrodes
W	mass rate of fuel consumption per unit volume by chemical reaction
x	space coordinate
Y	mass fraction of fuel
Z	modulus of source impedance
β	non-dimensional activation energy
δ	flame thickness
ΔT	temperature difference between flame kernel and surrounding gas
ε_a	ignition energy per unit area for plane source
ε_i	ignition energy for small spherical source
λ	thermal conductivity of gas
ρ	density of gas
ω_n	natural frequency of a simple tuned loop
Ω	energy released by combustion of unit mass of mixture

1 Introduction

Recently there has been some concern that incendive discharges may be drawn from plant structures acting as unintended receiving aerials to electromagnetic radiation. In particular, interest has focused on the compatibility of the St Fergus natural gas plant with the Royal Navy Wireless Transmitter Station at Crimond, and an attempt was made by the Health and Safety Executive to assess the radio-frequency ignition hazard at St Fergus on the basis of the guidance given in the relevant British Standard and its draft revision.[1,2,3] Unfortunately, no firm conclusion could be drawn; in fact, the hazard assessment served only to highlight inadequacies in the British Standard. One of the difficulties encountered was a lack of knowledge of the characteristics of ignition by r.f. breakflash discharges. This paper concentrates on this problem.

Some previous experimental work on the incendivity of r.f. breakflash discharges has been reported by Bittner.[4] He studied the effect of changing the impedance and frequency of resistive sources on the minimum

0033-7722/81/040175 + 12 $1.50/0

voltage required to ignite various fuel/air mixtures. Gehm and Dobritz[5] examined the effect of varying the quality factor, Q, of a parallel resonant circuit on the minimum voltage for ignition at 0·5 and 5 MHz. Howson and Butcher[6] investigated the frequency-dependence of the minimum power to ignite hydrogen/air mixtures. Some unpublished research by Gunnell at the Admiralty Surface Weapons Establishment reveals the effect of source impedance on ignition power.

Simultaneously with the present work, independent studies have been made by Widginton[7] and by Howson *et al.*[8] Widginton investigated the effects of different electrode materials and excitation frequencies; he used both a tuned pipe loop and a 50 Ω resistive source. He also performed some experiments from which he could deduce a time-scale for the ignition process. Howson *et al.* performed experiments with a 50 Ω resistive source; they found that propane, butane, and methane/air mixtures have similar r.f. ignition properties. They also confirmed Gunnell's results.

The research reported here is distinguished from most other work by the efforts made to simulate the real situation, both in the form of the electrodes between which the discharge is drawn, and the r.f. source that supplies energy to the discharge. Details of the apparatus and experimental method are presented in Sections 2 and 3. In the experiments discussed in Sections 4 and 5, r.f. sources of arbitrary form were used to identify minimum power and voltage requirements for the ignition of various gases and to investigate the influence of the excitation frequency and the shape, material and rate of separation of the electrodes. These experiments revealed the importance of the form of the r.f. source, so the authors proceeded to study more precisely defined sources. In Section 6 the variation of ignition power with source impedance for resistive sources is described. The resistive r.f. source was used to examine the effect of fuel/air ratio on the minimum power for ignition. Section 7 is an account of work with sources that simulate real plant structures. In Section 8 an order of magnitude analysis of the ignition process is performed; this helps to explain some of the experimental results.

2 Apparatus

The apparatus is shown schematically in Fig. 1. The combustion chamber is a thick-walled brass cylinder with internal dimensions of 80 mm diameter and 115 mm length. It is mounted on an insulating board, but is electrically connected to the screen of the r.f. power cable. The fixed 'live' electrode is mounted on a low-capacitance PTFE boss and connected directly to the r.f. terminal on the outside of the chamber. The moving 'earth' electrode passes through 'O' ring seals in the opposite wall of the chamber. A metal bellows completes the electrical circuit so that the chamber and electrodes are coaxial. Ports are provided for a pressure transducer, a pressure switch, a bursting disk, the gas supply, and observation windows. The gas feed-line to the chamber has a flame trap and a nylon insulating section.

The motion of the moving electrode is controlled by a pneumatic drive. A solenoid valve, operated by a low-frequency (approximately 1 Hz) square-wave generator and relay logic, switches high-pressure air onto alternate sides of a piston. Piston venting by bleed valves allows separate control of the speed of make and break strokes.

Gas composition is carefully controlled; the required mixtures are prepared by partial pressures in a mixing vessel and then released into the previously evacuated combustion chamber. It is thus possible to perform experiments at any desired pressure, though all work described in this paper has been at atmospheric pressure. Except where stated otherwise, the most ignitable mixtures of hydrogen (21% by volume), ethylene (7·8%), or methane (8·3%) and air were used.

The tips of the electrodes can be varied by screwing the desired pieces onto the ends of the electrode rods. The shapes of the electrode tips are shown in Fig. 2. Two basic systems were used: true breakflash and scrapeflash.

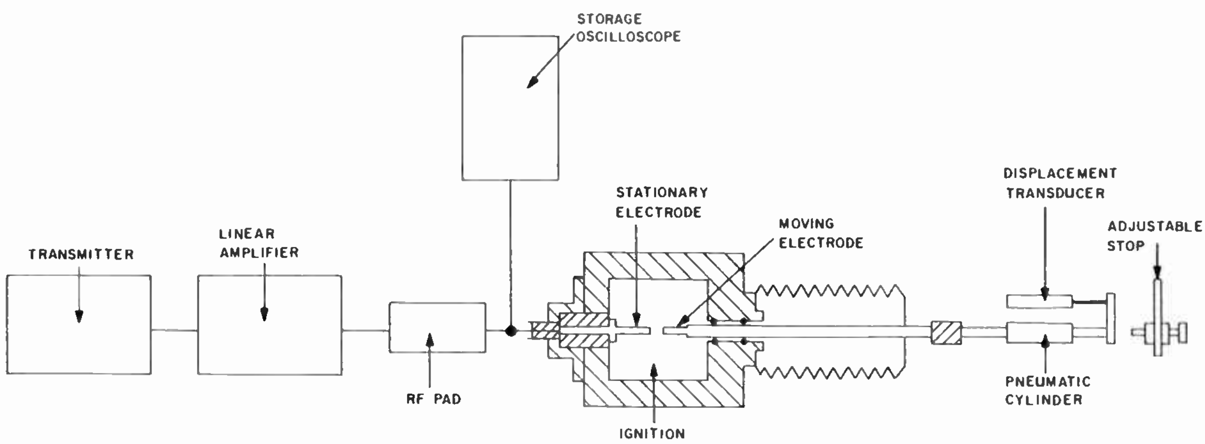
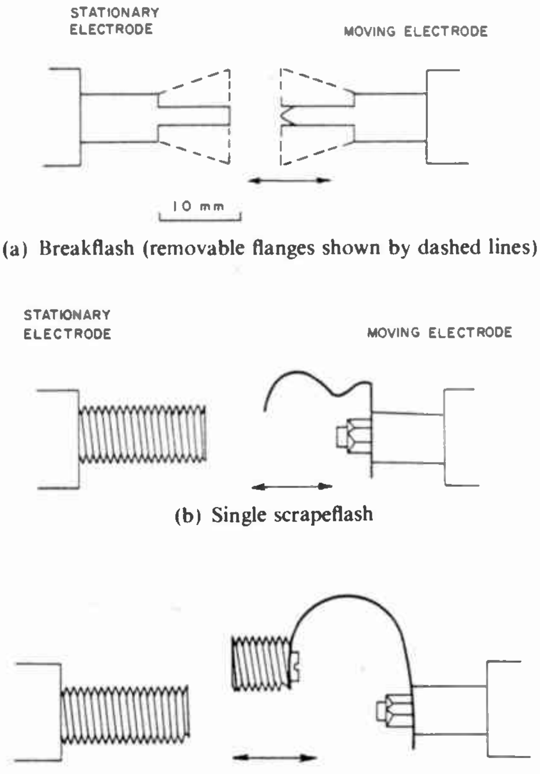


Fig. 1. R.f. ignition test apparatus.



(a) Breakflash (removable flanges shown by dashed lines)

(b) Single scrapeflash

(c) Double scrapeflash

Fig. 2. Electrode configurations.

In the true breakflash arrangements two blunt or one blunt and one pointed electrode meet end on (Fig. 2(a)). PTFE flanges can be fitted to these electrodes so that flame quenching effects may be investigated. In the scrapeflash arrangements a threaded stud or a plate with a rough surface is scraped either by a spring or by a second threaded stud mounted on a spring (Figs 2(b),(c)). The spring electrodes were made from $6 \times 0{\cdot}4 \times 35$ mm pieces of spring steel. The electrode system avoids the limitations on electrode shape and rate of separation found in the IEC intrinsic safety test cell used in almost all other work. In this work, an attempt has been made to make the electrodes more representative of metal objects that might be found in petrochemical plant than the electrodes used in the IEC device, in which a fine wire brushes over a grooved plate.

The r.f. source (i.e. all the r.f. supply circuitry external to the combustion chamber) consists of a transmitter (Trio-Kenwood TS-280) followed by a linear amplifier (Trio-Kenwood TL-922) and an output r.f. pad as shown in Fig. 1. The linear amplifier has a tunable output circuit with variable 'plate' and 'load' capacitors. The r.f. pad may be any required combination of resistors, inductors and capacitors, depending on the purpose of the experiment. The r.f. pads used fall into three general groups:

(i) In its simplest form the r.f. pad was merely a series low-inductance resistor whose value could be varied to alter the source impedance. When the series resistance is small, the linear amplifier output circuit may significantly affect the discharge.

(ii) Combinations of series and shunt resistors were used as the r.f. pad when the source impedance was required to approximate a pure resistance.

(iii) Combinations of resistive and reactive components were used to produce sources that simulate the r.f. impedance of real plant structures.

The r.f. pad is connected as close as possible to the combustion chamber to minimize stray capacitance at the chamber to about 8 pF. Current and voltage probes (Tektronix P6302 and Tektronix P6007, respectively) are fitted at the r.f. terminal of the fixed electrode on the combustion chamber. This is as close as possible to the discharge without the probes being exposed to the combustion. The outputs from the current and voltage probes and from the displacement and pressure transducers are recorded on an oscilloscope (Tektronix 7633 or 7844). At slow sweep rates (e.g. 1–10 ms per division) the current and voltage envelopes are recorded, whereas at faster sweep rates more detailed studies can be made (over an interval in the discharge) of the discharge current and voltage and of their phase relationship. The output from a photomultiplier tube aimed at the gap between the electrodes is also recorded on the oscilloscope. This gives a measure of the time variation of light output from the discharge and, if ignition occurs, from the resultant flame front.

The moving electrode control pulse also switches the transmitter, so that this is off during the make stroke and comes on just before the electrodes start to move apart. Simultaneously, the number of separations of the electrodes is recorded on mechanical counters. When ignition occurs, a pressure switch disables the control system so that electrode motion and r.f. generation cease. The experimental gas may then be changed and the system restarted.

3 Experimental Procedure in the Ignition Experiments

The open-circuit voltage, V_0, found with separated electrodes and no discharge, and the short-circuit current, I_s, with the electrodes together, are two major parameters of the r.f. circuit supplying power to the discharge. For each set of experiments a particular value of apparent source impedance, $Z = V_0/I_s$, is chosen; the value is set either by adjusting the linear amplifier tuning or by changing the components in the r.f. pad. Having set a particular value of Z, a line of roughly constant gradient which passes through the origin in V_0, I_s space, may be explored by adjusting the output power level of the amplifier.

This procedure was followed for various values of Z so that the V_0, I_s space was systematically examined for different gas mixtures, excitation frequencies and electrode arrangements. In this way the values of V_0, I_s for which ignition could occur were identified. The use of V_0, I_s, Z simplifies the discussion of detailed discharge processes. Reference is also made to $V_0 I_s/8$ (where V_0 and I_s are peak values), the power that the source can induce in a perfectly matched load. The use of matched-load power avoids the difficulty of measuring instantaneous power levels in the discharges. This approach also simplifies the problem of hazard assessment, since V_0, I_s are the properties of plant structures behaving as r.f. sources that can most readily be measured.

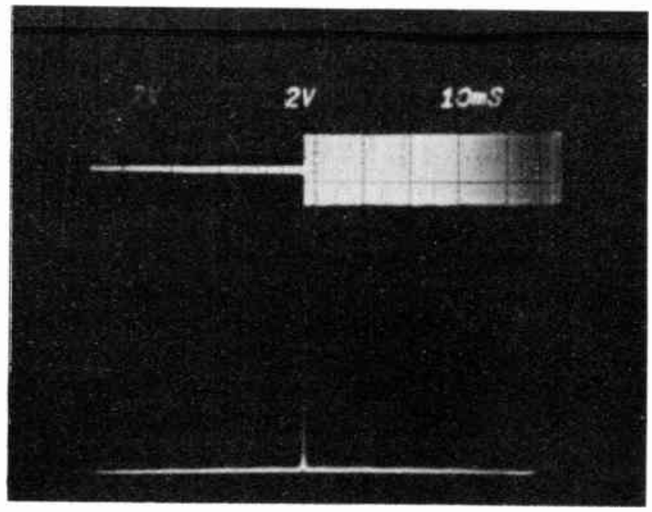
4 Experiments with True Breakflash Electrodes

In this Section, some experiments performed with the true breakflash electrodes will be discussed. The V_0, I_s space was examined as described above in order to identify ignition criteria. The r.f. pad was the series r.f. resistor arrangement. Similar magnitudes for the impedance of the r.f. source were obtained by combining different resistances with the different settings of the amplifier output tuning. In this way, any influence on the discharge of the complex form of the source impedance would be discovered. The effects of frequency and electrode shape, material and rate of separation were also studied. However, the general nature of the r.f. discharges will be discussed first.

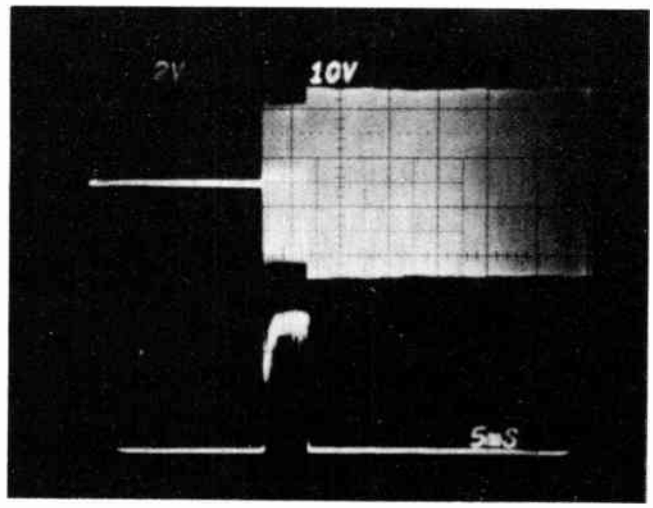
4.1 The Nature of R.F. Discharges in the Range 1–30 MHz

In the true breakflash arrangement the electrodes are initially in contact and carrying a current. Just prior to electrode separation, the current is extremely constricted as it flows through the last points of contact. The resultant molten metal bridges the gap between the electrodes and temporarily prevents the final break. Because of the high field strength, the copious thermionic emission and the presence of metal vapour due to the local heating, a 'short arc' is established when the break is eventually achieved.

The initial short arc persists only for the first stage of electrode separation, a distance of a few micrometres. At greater separations, the discharge transforms into a normal long arc, a glow, or an arc and thence to a glow—the type of discharge depends on the electrodes and the impedance of the driving circuit—or, if the driving voltage is inadequate, the discharge will cease. This is illustrated in Fig. 3. The top trace shows voltage across the electrodes, the lower trace shows light output. In Fig. 3(a) the voltage is too low for the discharge to persist; in Fig. 3(b) the voltage is higher and the discharge is sustained for several milliseconds. A long arc or glow will persist only if the voltage at the electrode tips exceeds a minimum value of 300–350 V pk.



(a) Short arc only, $V_0 < 300$ V pk



(b) Sustained discharge. $V_0 > 300$ V pk

Fig. 3. Voltage between breakflash electrodes and output from photomultiplier tube.

The reason for this minimum voltage lies in the nature of the discharges in this range. As shown by Schwab,[9] the characteristics of atmospheric pressure r.f. glow and arc discharges are very similar to those of the corresponding d.c. discharge types. The variation of voltage with time over a few cycles is shown in Fig. 4. At the end of each half-cycle of applied voltage the r.f. discharge is quenched and must be re-ignited in the following half-cycle. The minimum voltage for re-ignition in air is 300–350 V; thus the applied voltage must exceed about 300 V pk. After re-ignition the discharge voltage is high (> 275 V) for glows and low (< 30 V) for arcs. The type of discharge obtained depends on the electrodes and the external circuit impedance. With the fairly large electrodes (2–3 mm diam.), moderate discharge currents (< 3 A) and short duration discharges (< 30 ms) of the present experiments the discharge is normally a glow. However, short periods (about 1 ms) of arc discharge are observed, particularly just after electrode separation.

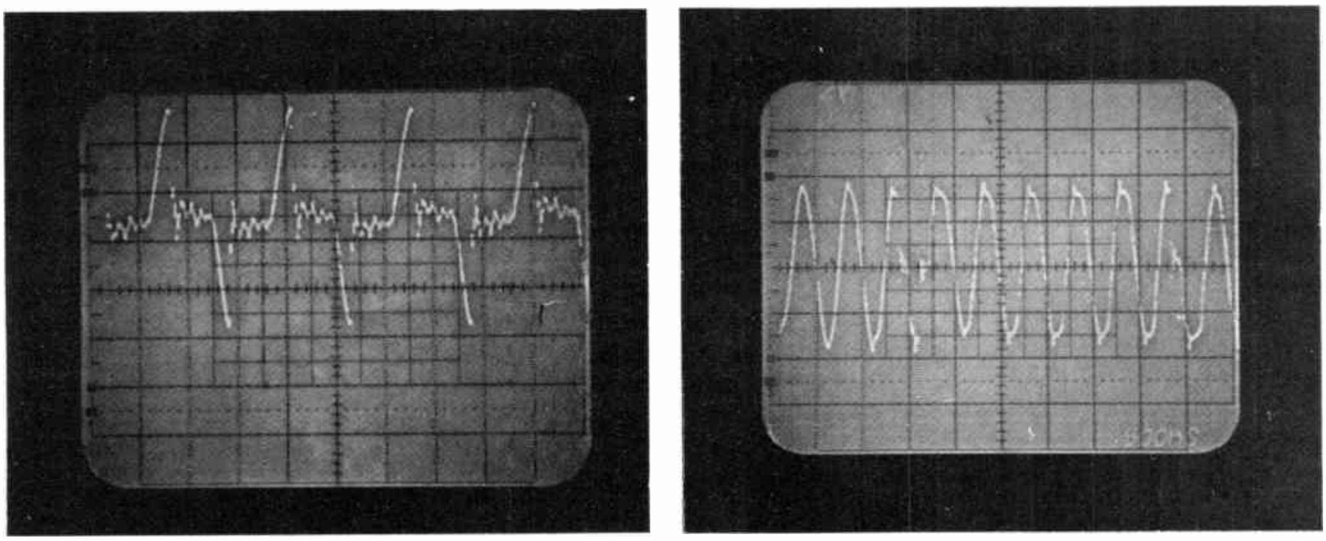


Fig. 4. Variation of voltage with time in sustained r.f. discharges.

4.2 Incendivity of R.F. Discharges: The Effect of Open-circuit Voltage and Short-circuit Current

Open-circuit voltage, V_0, and short-circuit current, I_s, provide some description (though by no means a complete one) of the driving circuit. If V_0 and I_s are peak values, then the maximum power the source can induce in a load is $P = V_0 I_s/8$, and the impedance of the source is $Z = V_0/I_s$. In Figs. 5 and 6, V_0 and I_s values for ignition and non-ignition of ethylene/air and methane/air mixtures at 2 MHz are plotted. The Figures show that in experiments with breakflash electrodes and line resistances of greater than 30 Ω it has been impossible to ignite hydrocarbon/air mixtures with electrode voltages of less than 300 V pk. This result is in broad agreement with those of Bittner for methane, propane and ethylene, Gehm and Dobritz for propane and Gunnell for methane. It appears that the initial short arc stage of the discharge cannot transfer enough energy to ignite ethylene, propane or methane/air mixtures, given the source impedances of the various experiments. To transfer enough energy to the gas a sustained discharge, and hence a voltage between electrodes greater than 300 V pk, is required. The source impedances of the present and the cited experiments fall in the range 50–3000 Ω. Obviously, the energy in the first stage of the discharge could be increased by further reducing the source impedance. However, impedances of much less than 50 Ω are unlikely to be encountered in structures that form the more effective receiving aerials.

Unfortunately, such a simple voltage criterion cannot be applied to hydrogen/air mixtures; the writers' incomplete results for hydrogen/air mixtures, and those of Bittner, both indicate that they may be ignited with voltages less than 300 V pk. Presumably because of the very low ignition energy of hydrogen, the initial short arc can transfer enough energy to induce ignition.

Apart from the minimum voltage line, the other boundary on the ignition region shown in Figs. 5 and 6 is a minimum power line. The power, P, that could be induced in a matched load (which the discharge is not) on these lines is 9 W for ethylene and 12 W for methane. Unfortunately, it is difficult to operate in this low-power,

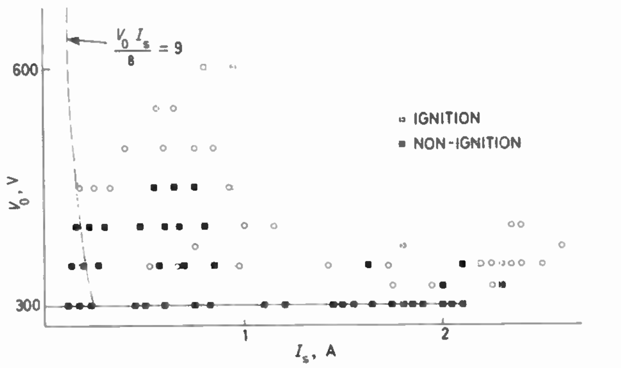


Fig. 5. R.f. breaksparks in 7·8% ethylene/92·2% air mixtures (by volume). True breakflash electrodes.

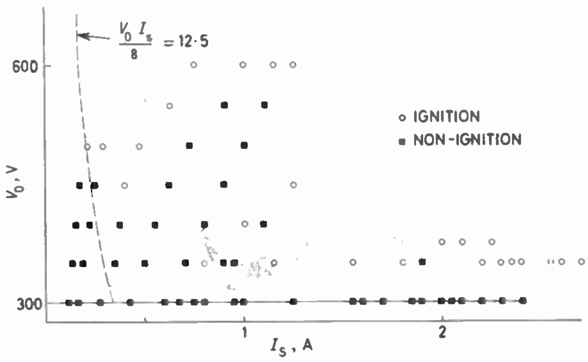


Fig. 6. R.f. breaksparks in 8·3% methane/91·7% air mixtures (by volume). True breakflash electrodes.

high-voltage region. To reduce the power supplied to the discharge it is necessary to increase the impedance of the driving circuit to several thousand ohms, which then becomes comparable with the capacitive impedance of the combustion chamber (10 kΩ at 2 MHz). Since the impedance of the chamber is in parallel with the discharge, it then becomes impossible to achieve high voltages across the discharge. In view of this difficulty, these values may not be particularly accurate. However, the results are consistent with the ignition powers of 7 W and 10·5 W obtained by Widginton for ethylene/air and methane/air mixtures.

4.3 The Effect of the Driving Circuit

Figures 5 and 6 show that, under some circumstances, it is possible for the gas to fail to ignite after 50 attempts, even though the open-circuit voltage, V_0, and short-circuit current, I_s, lie deep in the ignition zone. Though V_0/I_s specifies the magnitude of the source impedance it does not specify its form; this can be important.

A simple tuned loop circuit has both a transient and a steady-state response; the ratio of the time scale of decay of the transient to the time period of the steady-state oscillation is the quality factor, Q $(= \omega_n L/R)$, of the circuit. If Q is small, the circuit reaches steady-state (i.e. recovers from any disturbance) in less than one cycle; if it is large, this takes several cycles. The repercussions for an r.f. discharge circuit are illustrated in Fig. 7; when the circuit takes several cycles to recover from the re-ignition of the discharge, re-ignition cannot be repeated until several half-cycles have passed. Because of this, both in the writers' experiments and in those of Gehm and Dobritz, some circuits have been found to be less effective than others in transferring energy into the gas.

In these experiments the source impedance of the driving circuit has been varied both by changing the resistance of the r.f. pad and by changing the output

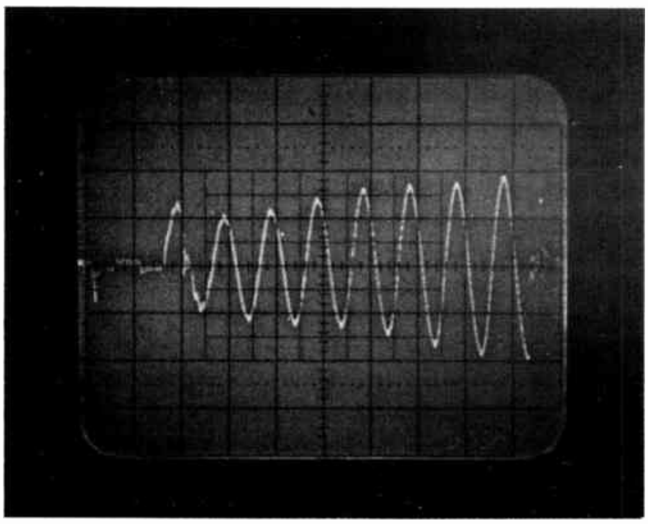


Fig. 7. Voltage variation with time. Here the circuit takes several cycles to recover from discharge re-ignition, so re-ignition can occur only in a few half-cycles.

tuning of the linear amplifier; the latter effectively changes the amount of capacitance and inductance in the circuit. Thus, the Q of the circuit was varied to some extent independently of the source impedance. This effect has not been quantified but is undoubtedly responsible for the variation in incendivity observed between different sources of the same impedance magnitude.

A second effect of the Q of the circuit, which is sometimes found when the line resistance is reduced below 50 Ω, is voltage overshoot. On separation of the electrodes a short arc forms; if the open-circuit voltage is below 300 V pk the discharge is quickly extinguished. However, if the line resistance is sufficiently low a transient voltage amplification can occur; the voltage at the electrodes may exceed the open-circuit voltage of the source and may also exceed the 300 V pk required to sustain a discharge. This phenomenon will be discussed further in Section 5.

4.4 The Effect of Frequency

The discussion so far has centred on results at 2 MHz, where most of the writers' work has concentrated. However, results at 15 and 21 MHz show general agreement with the 2 MHz work, and we conclude that the results are generally valid for the range of frequencies 2–21 MHz. This is not unexpected, since the nature of the discharge does not change over this frequency range, and the period of one r.f. cycle remains short compared with any ignition time-scale.

4.5 The Effect of Electrode Material, Shape and Rate of Separation

Electrodes of the breakflash type made from mild steel, rusty mild steel, stainless steel, copper, cadmium and zinc have been used. The variation in material has had no significant effect on the minimum voltages or minimum powers required for ignition. The result for the rusty mild steel electrodes may be misleading since, because of the nature of the contact in the true breakflash arrangements, the rusty surface was rapidly removed.

The breakflash type of electrode have either pointed or blunt tips. The difference had no detectable effect on the minimum voltage or minimum powers required for ignition. The addition of PTFE flanges to the electrodes had a sigificant quenching effect on ignition, and the minimum power required for ignition was more than doubled. Observation through the windows of the test chamber revealed that although the discharge induced a small flame kernel at the same power levels as before, this flame kernel was quenched before it could propagate beyond the edge of the flanges.

Over the wide range of rates of electrode separation possible with the present experiment, no variation in the minimum powers or minimum voltages required for ignition was observed. This is in expected contrast to observations (unpublished) with a pulsed radar-frequency source.

Table 1

Ignitions in 7·8% ethylene/92·2% air mixtures (by volume).
Fixed amplifier tuning circuit component values (plate 3·5; load 4)

	Value of resistance in series with electrodes								
	0 Ω			50 Ω			100 Ω		
	V_0, V	I_s, A	$V_0 I_s/8$, W	V_0, V	I_s, A	$V_0 I_s/8$, W	V_0, V	I_s, A	$V_0 I_s/8$, W
Rusty mild steel scrape	100	1·0	13	150	1·4	26	200	1·4	34
Clean mild steel scrape	200	2·3	56	250	2·4	75	300	2·1	79
Rusty mild steel/copper break	250	2·9	91	250	2·4	75	300	2·7	79
Clean mild steel break	250	2·7	84	300	2·9	107	325	2·3	91
Double rusty mild steel scrape	200	2·3	57	—	—	—	—	—	—

5 Experiments with Scrapeflash Electrodes

Some experiments have been performed in which the true breakflash electrodes were replaced by the scrapeflash electrodes shown in Figs. 2(b) and (c). As in the experiments described in Section 4, the r.f. pad was a resistor connected in series with the amplifier. Table 1 allows some comparison between the minimum open-circuit voltages required for the ignition of ethylene/air with different electrodes with fixed settings of the driving circuit. It should be noted that:

(i) The open-circuit voltage requirement is lower with clean, scraping electrodes than with clean, breakflash electrodes; a steel spring scraping a rusty stud has the lowest open-circuit voltage requirement of all.

(ii) The voltage requirement is higher for two scraping rusty studs than for one rusty stud and a spring, presumably because of the increased quenching.

(iii) As line resistance increases, the open-circuit voltage requirement increases for all systems.

A wider selection of results for the steel spring/rusty stud scrapeflash is shown in Fig. 8. It is seen that the lowest open-circuit voltage for ignition has fallen to 75 V pk. It can also be deduced that the lowest power found is 13 W, which agrees reasonably well with the value obtained with high impedance sources connected to the true breakflash. Clearly, a rusty steel electrode scraped by a steel spring provides the most sensitive electrode arrangement. It appears that the voltage criterion is relaxed for this arrangement, presumably because the low work function of the metal oxide aids the production of electrons. This observation is in general agreement with that of Widginton.

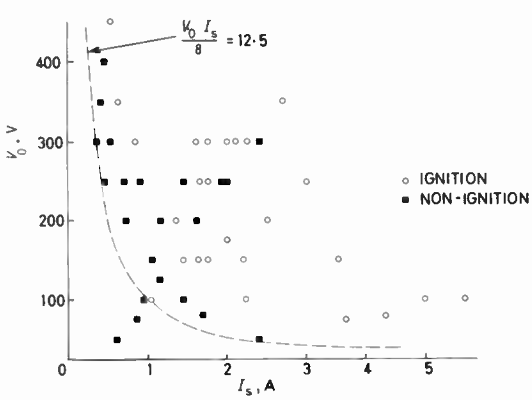


Fig. 8. R.f. breaksparks in 7·8% ethylene/92·2% air mixtures (by volume). Single rusty scrapeflash electrodes.

Figure 9 shows a voltage envelope trace and a trace on a much faster time-base. The latter reveals a similar behaviour to that attributed to high Q effects in Section 4.3. Here it is seen that after the short arc disappears in the period following electrode separation, the high Q effect leads to voltage amplification to values greater than the open-circuit voltage. This voltage amplification is seen as the spikes in the voltage envelope. This explanation is supported by the effect of line resistance, which progressively damps out the voltage spikes, thereby increasing the open-circuit voltage required for ignition (Table 2).

Table 2

Minimum ignition powers from methanol tanks equivalent circuit

	Highest non-ignition values			Lowest Ignition values		
	V_0, V	I_s, A	$V_0 I_s/8$, W	V_0, V	I_s, A	$V_0 I_s/8$, W
Methane/air	225	0·45	12·7	250	0·5	15·6
Ethylene/air	150	0·3	5·6	175	0·34	7·5

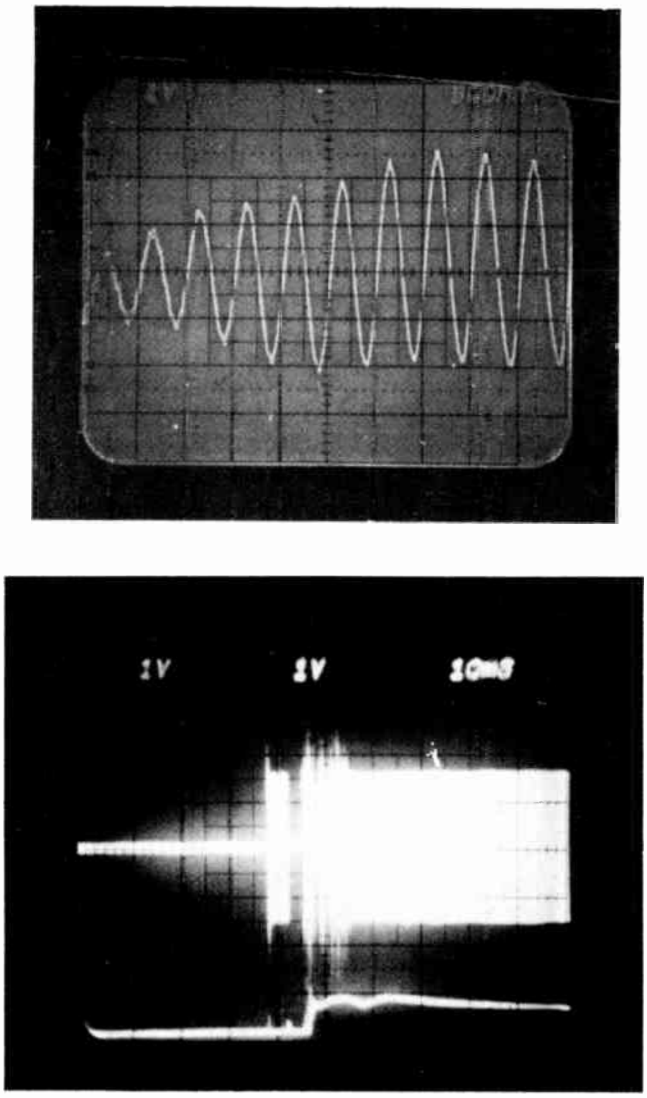


Fig. 9. Scrapeflash rusty steel stud/spring electrodes. Effect of voltage amplification. All traces are for the same driving circuit.
line resistance = 0 Ω, V_0 = 150 V, I_s = 3·5 A,
plate setting = 3·5, load setting = 4,
voltage scale = 100 V/div.

6 Experiments with Resistive Sources

In this Section, some experiments are described in which the r.f. pad was designed such that the r.f. supply approximated a pure resistance.

Figure 10 shows a plot of the matched load power required to ignite an ethylene/air mixture against the apparent source impedance for essentially resistive driving circuits. The results with Z greater than 500 Ω are extracted from the true breakflash experiments with clean mild steel electrodes described in Section 4.5. In the new experiments Z is less than 500 Ω and the electrodes consisted of a spring scraping a rusty plate.

No overshoots were found in these experiments on either the voltage or current traces. This is because the source is not a high Q circuit. Figure 10 shows that, as the source impedance falls, the matched load power required for ignition increases. This may be attributed to the decreasing stability of the discharge as the source impedance falls. A similar result has been observed by Bittner in his experiments with hydrogen/air mixtures.

Using clean mild steel, true breakflash electrodes and an essentially resistive source of high impedance (about 1400 Ω), the effect of fuel/air ratio on incendive power was investigated. Figure 11 shows matched load power for the ignition of methane/air mixtures; a similar curve was obtained for ethylene/air mixtures. The most easily ignitable mixtures are 8·3% by volume methane in air and 7·8% ethylene in air. These results are in agreement with those quoted by other authors.[4,7,8]

7 Experiments with Tuned Loop Sources Simulating Real Plant Structures

This Section describes the investigation of the incendivity of discharges generated with a rusty steel scapeflash; in these experiments, the r.f. pad was designed such that the supply simulates the lumped equivalent circuit of a plant structure. The equivalent circuits used were those given by the ERA[10] for the methanol tanks on the British Gas Corporation site and Process Stream 100 on the Total Oil Marine site at St Fergus.

The circuit shown in Fig. 12 was used to simulate the

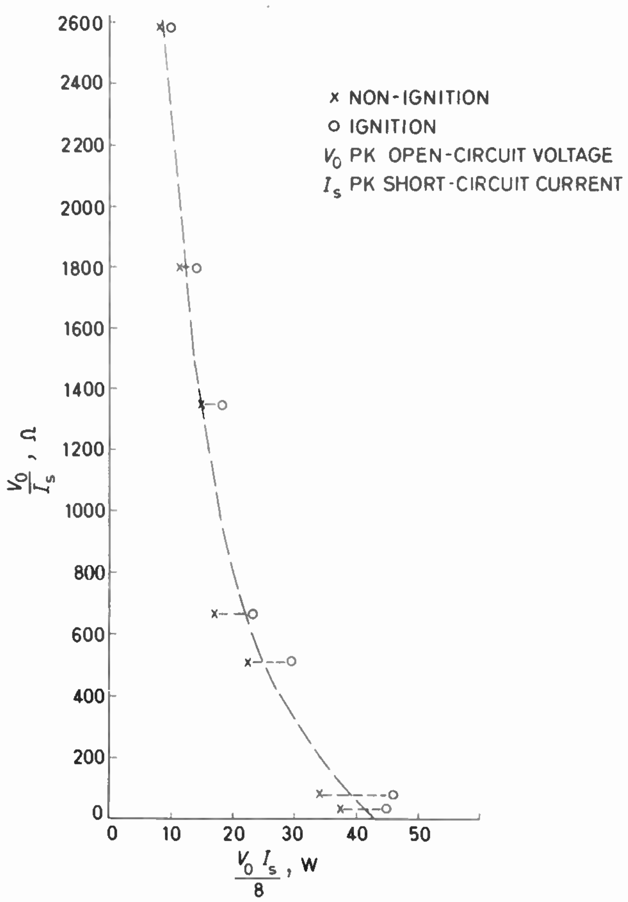


Fig. 10. Apparent impedance vs. power into a matched discharge (7·8% ethylene/92·2% air by volume)

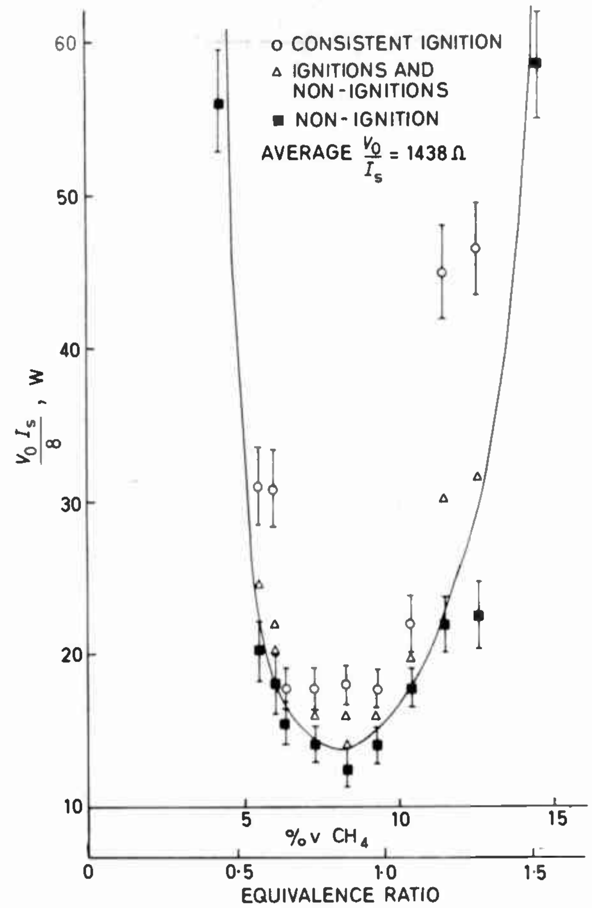


Fig. 11. Matched load power vs. %v methane/air mixture composition.

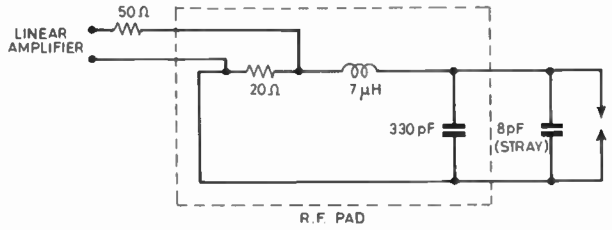


Fig. 12. Equivalent circuit of methanol tanks.

The circuit used to simulate Process Stream 100 is shown in Fig. 13. Since the ERA report[10] does not specify any values for the resistors R_2 and R_3, two different combinations were used. This circuit has two resonant frequencies. For a given power output from the transmitter there are voltage maxima at the electrodes at 1·83 MHz and 3·56 MHz. Again, these were independent of the setting of the linear amplifier outputs. The results for this circuit are recorded in Table 3. The maximum power output from the linear amplifier was insufficient for the ignition of methane/air mixtures at 3·56 MHz. However, the results for ethylene/air mixtures suggest that the same matched load power is required from the supply at both resonant frequencies.

The matched load powers required for the ignition of ethylene/air mixtures are about 7 W at 500 Ω (3·86 MHz) from the equivalent circuit of the methanol tanks, and about 15 W at either 236 Ω (1·83 MHz) or 1100 Ω (3·56 MHz) from Process Stream 100. These values do not show any simple relationship with the powers

methanol tanks as the r.f. supply to a discharge. It was found that maximum open-circuit voltage at the electrodes was obtained at a frequency of 3·86 MHz; this was independent of the output tuning of the linear amplifier. Oscilloscope traces of voltage and current reveal that there are no significant spikes on the voltage trace, but large overshoots are found on the current trace; this contrasts with the observations in Section 5.1. The highest incendive and lowest non-incendive conditions for ethylene/air and methane/air mixtures are listed in Table 2.

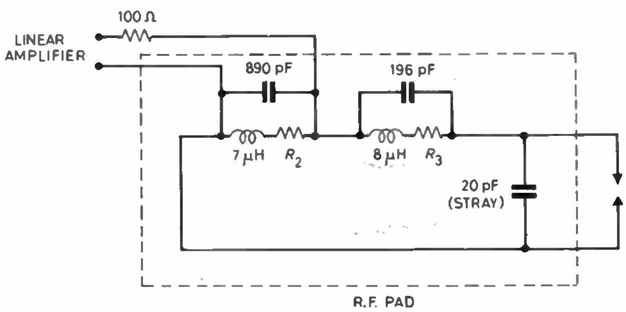


Fig. 13. Equivalent circuit of Process Stream 100.

Table 3

Minimum ignition powers from Process Stream 100 equivalent circuit

			Highest non-ignition			Lowest ignition		
R_2	R_3	Frequency, MHz	V_0, V	I_s, A	$V_0I_s/8$, W	V_0, V	I_s, A	$V_0I_s/8$, W
METHANE/AIR								
97	99	1·85	225	0·8	22·5	250	0·85	26
50	20	1·85	230	1·1	30	250	1·2	36
97	99	3·57	175	0·4	9			
50	20	3·57	400	0·34	17			
ETHYLENE/AIR								
50	20	1·85	160	0·68	13·5	170	0·75	16
50	20	3·57	350	0·32	14	375	0·34	16

required from resistive sources of similar impedance (plotted in Fig. 10). In particular, the simple loop equivalent circuit of the methanol tanks has a lower power requirement for the production of an incendive discharge. This must be due to the form of the source impedance.

8 Theoretical Discussion of the Ignition Process

A simple model of the ignition process in conjunction with an order of magnitude analysis is now used to derive some scaling laws. This should increase the understanding of the experimental results and aid extrapolation to r.f. sources that are not continuous wave.

It is assumed that the chemistry can be modelled as a one-step reaction, in which

$$\text{fuel} + \text{oxygen} \rightarrow \text{product} \tag{1}$$

and the rate of consumption of fuel (mass per unit volume per unit time) is

$$W = AY^n \exp\left(-\frac{E}{RT}\right) \tag{2}$$

where A and n are constants, E is the activation energy, R is the gas constant, T is the temperature, and Y is the mass fraction of fuel. Note that, from the Arrhenius rate law assumed in (2), W is exponentially small except at the largest values of T so long as $E/RT \gg 1$.

The one-dimensional transport equation for heat is

$$\underset{\substack{\uparrow\\ \text{rate of increase}\\ \text{in element}}}{\rho C_p \frac{\partial T}{\partial t}} + \underset{\substack{\uparrow\\ \text{convection out}\\ \text{of element}}}{\rho C_p u \frac{\partial T}{\partial x}}$$

$$= \underset{\substack{\uparrow\\ \text{diffusion into}\\ \text{element}}}{\frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right)} + \underset{\substack{\uparrow\\ \text{release by}\\ \text{chemical}\\ \text{reaction}}}{\Omega W} + \underset{\substack{\uparrow\\ \text{addition from}\\ \text{external source,}\\ \text{i.e. electric}\\ \text{discharge}}}{F(x,t)} \tag{3}$$

where C_p is specific heat, t is time, u is gas velocity in the x direction, ρ is density, λ is thermal conductivity, and Ω is the energy released per unit mass of fuel by combustion.

An analogous equation to (3) exists for the fuel concentration Y. However it is not required for the present discussion.

Equation (3) is commonly used in the study of premixed gas flames and ignition. For a steady flame observed in a co-ordinate system stationary relative to the flame front, (3) becomes

$$\rho C_p u \frac{\partial T}{\partial x} = \frac{\partial}{\partial x} \lambda \left(\frac{\partial T}{\partial x}\right) + \Omega W \tag{4}$$

So long as $\beta = E/RT_b$ is large (this is true for most hydrocarbon/air mixtures), the flame has the structure shown in Fig. 14. By balancing the convective and

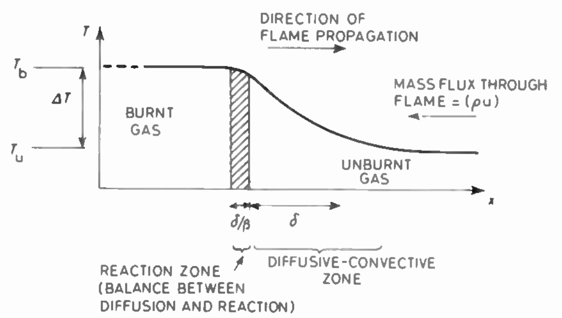


Fig. 14. Steady flame front.

diffusive terms in (4), order of magnitude analysis gives for the convective-diffusive zone

$$(\rho u) C_p \frac{\Delta T}{\delta} \simeq \left(\lambda \frac{\Delta T}{\delta^2}\right)$$

so the flame thickness is given by

$$\delta \simeq \frac{\lambda}{(\rho u) C_p} \tag{5}$$

Similarly for the reaction zone, balancing diffusion and reaction terms gives

$$\delta^2 \simeq \frac{\beta \lambda}{C_p W} \tag{6}$$

The laminar flame speed, S, is defined as the velocity of the unburnt gas relative to the flame front, so

$$S = \frac{(\rho u)}{\rho_u}$$

From (5) and (6)

$$S \simeq \frac{1}{\rho_u} \sqrt{\frac{W\lambda}{\beta C_p}} \tag{7}$$

For the ignition problem, return to equation (3) and consider a co-ordinate system stationary relative to the heat source (the discharge). For simplicity, the problem is treated as one-dimensional. It is assumed that the heated region around the discharge has a structure of the form shown in Fig. 15. For ignition, the heat release in the reaction zone needs to be of the same order as or

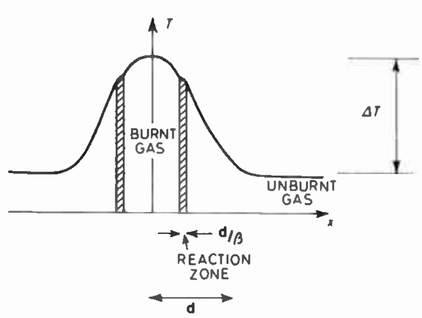


Fig. 15. Heated region around discharge.

greater than diffusion out of the zone, i.e.

$$\Omega W \gtrsim \frac{\Delta T}{d^2} \beta\lambda \tag{8}$$

where d is an appropriate length scale.
Ignition energy per unit area is

$$\varepsilon_a = d\rho C_p \Delta T \tag{9}$$

From (8)

$$\varepsilon_a \gtrsim \frac{C_p(\Delta T)^2}{d} \frac{\beta\lambda\rho}{W\Omega}$$

also $$\Delta T \gtrsim \frac{\Omega}{C_p}$$

so $$\varepsilon_a \gtrsim \frac{\beta\lambda\Omega\rho}{dW\,C_p}$$

From (5) and (6), for a steady flame

$$dW = \delta W = \beta S\rho$$

If this is approximately true for the ignition kernel, then

$$\varepsilon_a \gtrsim \frac{\lambda\Omega}{C_p S} \tag{10}$$

Thus, for a small spherical source, the minimum ignition energy should be

$$\varepsilon_i \simeq \frac{\lambda\Omega}{C_p S} d^2 \tag{11}$$

If d is the same order as the quenching distance (or the laminar flame thickness), then the expression given in (11) is identical to that suggested by Lewis and von Elbe[11] and found by Metzler[12] to be in very rough agreement with experiments.

In order to deduce ignition powers, a time-scale must be obtained for the ignition process. The relevant time-scale is provided by the diffusion term in equation (3). This is

$$t_i = \frac{\rho C_p}{\lambda} d^2$$

If d is taken to be of the same order as the quenching distance or laminar flame thickness, then

$$t_i = \frac{h\lambda}{\rho C_p S^2} \tag{12}$$

where h is a constant, of order unity.

A minimum ignition power, P_i, may now be deduced from (11) and (12)

$$P_i \simeq \frac{\varepsilon_i}{t_i} \tag{13}$$

$$P_i \simeq \frac{\Omega S}{\rho} d^2 \tag{14}$$

Table 4 gives some calculations based on the present analysis. The ignition times were obtained from equation (12) using experimentally observed values of flame speed and values of thermal diffusivity of 4×10^{-5} m²/s for hydrocarbon/air mixtures and 6×10^{-5} m²/s for hydrogen/air mixtures; the constant h was put equal to 3. The ignition powers were then calculated from equation (13) using measured values of minimum ignition energy rather than values obtained from equation (11). If some assumption is made about the fraction of the matched power (say 30%) that is actually dissipated in the gas, then the matched power required for ignition can be calculated. Table 4 shows that there is remarkably good agreement between experimentally observed values of ignition power and time and the order of magnitude calculations. One feature of the results in Table 4 is that minimum ignition power is much less sensitive than minimum ignition energy to composition changes. This is because the most ignitable gases tend to have shorter ignition times.

9 Conclusions

1. For mixtures of ethylene or less easily ignitable hydrocarbons with air, a minimum voltage between clean, metallic electrodes of about 300 V pk must be exceeded for ignition.
2. For ethylene/air and methane/air mixtures, minimum powers of about 7 W and 12 W, respectively, must be exceeded for ignition by discharges from the r.f. sources of optimum form.

Table 4

Measured and estimated ignition times and powers

Fuel	Measured minimum ignition energy, μJ	Calculated ignition time, t_i, μs	Calculated minimum ignition power, P_i, W	Calculated matched power assuming 30% efficiency, W	Measured ignition time, μs	Measured matched powers, W
Hydrogen	18	20	0·9	3	30†	2†
Ethylene	85	40	2·1	7	100†	7
Methane	280	110	2·6	9	100†	12

† From Widginton[7]

3. The form of the discharge circuit has an important influence on the power required for ignition. It appears that resistive sources of high impedance and tuned loops with Q of order 10 provide the most incendive discharges.
4. No significant change in r.f. ignition behaviour has been observed over the 2–21 MHz range.
5. The presence of flanges on electrodes has a significant quenching effect.
6. The rate of separation of electrodes is not important.
7. With the same driving circuit scraping electrodes appear to produce a slightly more incendive discharge than do true breakflash electrodes.
8. All the electrode materials behaved in much the same way, apart from rusty mild steel. This produced incendive discharges at much lower voltages than did clean metals; no voltage criterion was identified for rusty steel electrodes.

10 References

1 'Report of a Working Group on Radio-ignition Hazards at St Fergus, Scotland', Health and Safety Executive, 1978.
2 'Guide to Protection Against Ignition and Detonation Initiated by Radio-frequency Radiation', British Standard BS 4992: 1974.
3 'Draft Guide to Protection Against Ignition and Detonation Initiated by Radio-frequency Radiation', Draft revision of BS 4992: BSI draft for public comment doc. 76/27631 DC, September 1976.
4 Bittner, G., 'Über die Funkenzündung explosibler Atmosphäre im Frequenzbereich 1 kHz bis 10 MHz,' *PTB-Mitteilungen*, **86**, p. 26, 1976.
5 Gehm, K. H. and Dobritz, 'Zündmöglichkeit von explosiblen Gemischen durch Hochfrequenz-Energie', *Z. Arbeitsschutz*, **12**, p. 294, 1962.
6 Howson, D. P. and Butcher, G. H., 'Coaxial breakflash for r.f. ignition of flammable vapours', *Proc. Instn Elect. Engrs*, **122**, pp. 1453–4 1975.
7 Widginton, D. W., 'Ignition of Flammable Gases by Radio-frequency Discharges', RLSD, Health and Safety Executive, 1979. Also: 'Radio frequency ignition hazards; Part 1. Ignition of flammable gases by radio frequency discharges from tuned loops and 50 Ω resistive sources in the frequency range up to 10 MHz', *The Radio and Electronic Engineer*, **51**, no. 4, pp. 151–60, April 1981.
8 Howson, D. P., Butcher, G. H. and Excell, P. S., 'The ignition of various gas/air mixtures by sparks from 2 MHz or 9 MHz sources', *The Radio and Electronic Engineer*, **51**, no. 4, pp. 170–4, April 1981.
9 Schwab, H. A., 'Some properties of radio-frequency gas discharges in air at atmospheric pressure', *Proc. IEEE*, **59**, p. 613, 1971.
10 Progress Report: Analysis of results of measurements of induced RF voltage and power at the St Fergus gas terminal, ERA report no. 3477/1 (1979).
11 Lewis, B. and von Elbe, G., 'Combustion, Flames and Explosions of Gases' (Academic Press, New York, 1951).
12 Metzler, A. J., 'Minimum spark-ignition energies of 12 pure fuels at atmospheric and reduced pressure', NACA, RM E53H31, 1953.

Manuscript received by the Institution on 8th February 1980
(Paper No. 1979/MI 18)

The Authors

After completing his B.A. in natural sciences and Ph.D. in physical chemistry, **Jean Rosenfeld** did research in theoretical chemistry at Stockholm. In the United States he studied scattering theory at the University of Wisconsin and at Brown University. Since joining Shell Research, Dr Rosenfeld has been involved in numerous combustion problems and currently leads a research group in combustion physics.

David Strachan graduated in electrical engineering and electronics at the University of Liverpool in 1967 where he later received his Ph.D. in 1971. A lecturer at Liverpool in 1970/71, he was elected to a British Steel Corporation Fellowship from 1971/73. During 1973/78 he was a research officer with responsibility for the high power laboratory of the SRC arc research project at Liverpool University. Dr Strachan's research interest throughout this period was the fundamental behaviour of electric arcs relevant to the steel and switchgear industries. Since joining Shell Research in 1979, his interests have included the applications of r.f. and infra-red physics and, more recently, industrial robotics.

Paul Searson commenced his physics course at Loughborough University in 1976 and graduated last year. During his course he gained industrial experience with Rolls-Royce and Shell Research. His work has involved various applications of lasers and the transfer of r.f. energy into incendive electrical discharges.

Peter Tromans graduated in engineering from Cambridge University in 1973; in 1978 he received his Ph.D. at Cambridge for research in fluid mechanics. His industrial career has been spent with the British Steel Corporation and his present employer, Shell Research. His research interests lie in fluid mechanics, applied thermodynamics and combustion; at present Dr Tromans is particularly interested in the ignition of gases by electric discharge and the subsequent flame development.

UDC 621.317.32/37.029.5: 66.07

Indexing Terms: Electric measurements, voltage, power, Gas plants, R.f. hazards, Electromagnetic compatibility

Measurements of radio frequency voltage and power induced in structures on the St Fergus gas terminals

A. J. MADDOCKS,
M.Tech., B.Sc.*

and

G. A. JACKSON,
B.Sc., C.Eng., F.I.E.E., F.I.E.R.E.*

SUMMARY

In order to assess the compatibility of the Crimond RN wireless station with the nearby gas processing plants at St Fergus, a programme of experimental investigation was put into operation whereby the potential hazard due to radio frequency induced ignition could be assessed from direct measurements of induced power in the structures. This paper describes those investigations, the results that were obtained, and the conclusions that were drawn.

* *ERA Technology Ltd., Cleeve Road, Leatherhead, Surrey, KT22 7SA*

1 Introduction

At the request of the Steering Committee on radio frequency ignition hazards at St Fergus, Scotland[1] a series of tests was carried out at the St Fergus Gas Terminals in October and November 1978 in order to evaluate the radio frequency voltages and powers induced in the structures due to the transmitters at the nearby Crimond RN radio station. These data[2] were to be evaluated by the Technical Sub-Committee appointed by the Steering Committee, using available information on ignition criteria at radio frequencies, so that an assessment of the potential hazard at St Fergus could be made. The investigations were organized and co-ordinated by the Health and Safety Executive who placed the contract for this research work.

A large number of structures was selected by the Technical Sub-Committee for examination both on the grounds of likely high efficiency as loop or vertical type aerials, and also because some of them were in hazardous areas. The majority of the tests were made at breaks in the structures where direct measurements of induced voltage and current could be made. The structures were also resonated with external tuning components which enabled the available power to be calculated. Also, where possible, an impedance meter was used to measure the input impedance to the structures. The test procedure involved taking measurements at a low level of power (2 kW) from the nine h.f. transmitters at Crimond at a large number of locations on the Total Oil Marine (TOM) site. The transmitter power was then increased progressively, and at each stage measurements were made at selected sites until the full power of 20 kW per transmitter was obtained. In addition to the r.f. measurements, an IEC breakflash apparatus was coupled to many of the resonant structures, where it was attempted to ignite a hydrogen/air gas mixture with the power available from the structure. Further tests were carried out at the British Gas Corporation (BGC) and Shell sites at transmitter powers of 20 kW.

It was possible from these results to obtain valuable information on the way in which the structures interacted with the incident electromagnetic field and to examine in detail the characteristics of the more efficient structures. This enabled a confident prediction to be made of the induced voltages and available powers expected when Crimond would be operating at its full capacity of sixteen h.f. and three l.f. transmitters.

2 Measurements

Over 40 structures were examined and many of them were tested at several different levels of transmitter power. At each particular structure, and at each of the Crimond transmission frequencies, measurements were made of open-circuit voltage, short-circuit current and resonant current through an external tuning reactance. In addition, a measurement of input impedance was

0033–7722/81/040187+08 $1.50/0

made in structures where the level of induced voltage† was sufficiently low not to affect adversely the meter indication. Field intensity measurements were also made, usually at a location about 5–10 metres from the structure so that the re-radiated field due to currents induced in the structure was minimized. Having completed tests at individual frequencies using the selective receiver, a measurement of the cumulative voltage was made with an oscilloscope, both under open-circuit conditions and with an external tuning reactance across the terminals. The reactance was adjusted for maximum voltage indication.

An IEC breakflash apparatus complying with the requirements of IEC 79–3 and described in BS 5501: Part 7: 1977 was used to determine the ignition capability of the structure concerned. It comprised a cadmium disk with tungsten wires and used a 21% hydrogen/air mixture as the test gas, which was the optimum concentration for ignition by electrical discharges. In order to comply with safety recommendations, the test cell was surrounded by a blanket of nitrogen gas under continuous flow. The interior of the cabinet surrounding the gas chamber was painted black in order to assist with the observation of sparking at the electrodes.

The breakflash was connected by short leads in parallel with the tuning component required to resonate the structure. The tuning was adjusted to produce the maximum voltage across the breakflash, as observed by monitoring with an oscilloscope, the internal breakflash electrode connection being open circuited. The make/break mechanism was operated with the test gas flow for a minimum of 5 minutes. The sensitivity of the cell was checked with a standard calibration circuit prior to the commencement of each series of tests.

In order to comply with the agreed safety procedure, the measurements on the Total Oil Marine site were commenced with each of the nine h.f. transmitters at Crimond operating at 2 kW, with the alternative of only one transmission at 20 kW. Following a survey of about 30 structures, the transmitter powers were increased to 4 kW with further increases after additional tests to 8 kW and finally 20 kW. The subsequent measurements on the British Gas Corporation and Shell sites were then made at 20 kW power outputs. Following each increase in h.f. transmitter power level, measurements of induced voltage and power were made on a telescopic crane on the Shell site to ensure that the induced voltage and power did not exceed the levels agreed in the Technical Sub-Committee before carrying out further tests on the structures on other sites.

Measurements on the TOM site were made in October 1978. The tests on the BSC and Shell sites were carried out in November 1978 after some changes had been made in the frequency allocation of the directional aerials.

From the voltage and current measurements on the structures at individual frequencies it was possible to calculate parameters relating to the characteristics of the structures, such as: apparent tuning coefficient(Q'), apparent effective height(h'_e), circuit impedance($R'+jX'$), the available induced power(P_i), and the efficiency(η) of the structure as a radio receiving element.

† From transmissions other than Crimond, which was shut down during the impedance measurements.

3 Results

3.1 Radio Frequency Measurements

The accumulated data were examined in the light of the transmission capability of the Crimond radio station. The aerials for transmission at frequencies below 3 MHz were not designed for this frequency range and as a consequence were somewhat inefficient. In order to make an accurate assessment of the induced voltages and powers resulting from efficient aerials some correction factors had to be applied. However it is useful to put the values measured into context by examining the results obtained on the most efficient structures. Table 1 presents the highest voltages measured at any single frequency and for the total combination of all transmissions:—

Table 1

	Structure	20 metre Crane	Methanol Tanks
Highest voltage at a single frequency	Frequency (MHz)	2·8	3·3
	Open-circuit volts (peak)	6·3 V†	2·5 V
	Resonant current (peak)	20 mA†	10 mA
	Available power (mean)	15·8 mW†	2·2 mW
Cumulative voltage (9 transmissions 20 kW each)	Open-circuit volts (peak)	28 V	8·5 V
	Resonant volts (peak) (structure resonated at one frequency)	36 V	10·5 V

† Measurements made in October 1978, all other values obtained in November 1978.

Both the crane and the Methanol Tanks structure achieved their maximum efficiency within the band of frequencies transmitted from Crimond. The voltages in the Table were the highest obtained in any of the tests and most other structures which were examined produced voltage levels which were significantly less than these values.

The measurements of voltage that were made provided a valuable indication of how the various individual frequencies contributed to the cumulative effect both in amplitude and waveform. For the fixed structures, the peak of the cumulative voltage was within 1·5 dB of the sum of the individual voltages, and for the cranes it was within 2·5 dB. This indicates that voltage addition took place in the structures over quite a wide frequency range and that the sum of the individual voltages can be used to obtain a reasonably accurate assessment of the peak of the accumulated wave.

The cranes produced the highest voltage readings of all measurements made, yet no readings exceeded 36 volts (peak) under the Crimond transmission conditions that existed during the testing period.

Measurements were made on a crane on the Shell site under the same physical condition for a number of transmitter powers and the peak open-circuit cumulative voltages were as follows:

Transmitter Power (kW)	2	4	8	20
Open Circuit Voltage (V_0)	6·5	9	13	18

The voltages increased proportionally to the square root of the power and enabled fairly accurate predictions to be made of changes of voltage with transmitter power variations.

3.2 Breakflash Cell Tests

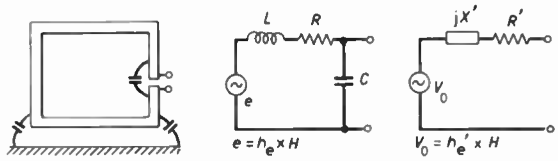
No ignitions of the hydrogen/air gas mixture were obtained in the IEC Breakflash Cell arising from induced r.f. energy in any of the structures. Very faintly visible intermittent sparking was observed in the cell for only one structure, a crane with a 20 metre jib length, with all nine h.f. transmitters each operating at 20 kW; the tuned voltage under these conditions was 36 V peak. This voltage failed to achieve ignition of the test gas.

4 Characterization of Structures

The measurements of open-circuit voltage, short-circuit current and resonant current enabled calculations of the input impedance of the structure to be made in all cases. For many structures direct measurements of input impedance were also made using the impedance meter but it was difficult to obtain reasonable or consistent results with the meter on structures where high induced voltages existed; this was obviously more of a problem on the more efficient structures. However where measurements were made with the meter, generally good agreement was obtained with the values calculated from the voltage and current measurements. The analysis of the impedance information is an essential factor in arriving at a more complete understanding of the behaviour of real plant structures at radio frequencies, and has enabled equivalent circuits to be derived which have assisted in the assessment of incendivity in the laboratory. A number of structures including loop and monopole types and also cranes have been examined and some steps have been made towards producing equivalent circuits.

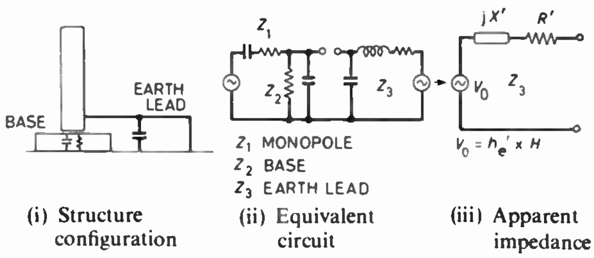
4.1 Loop Structures

All the loop type structures possessed similar characteristics to those shown in Fig. 1. The loop shown



1. Loop Structures

The term jX' is positive below self resonance, 0 at reactance resonance and negative above self resonance.



2. Vertical Structures

In many cases, owing to the low base impedance Z_2, the input impedance is predominantly that of the earth lead Z_3, and the treatment given to loop type structures applies.

Fig. 1. Simple equivalent circuits of structures

has stray capacitance across the point of measurement and to ground, which as a first attempt can be represented as a lumped capacitance in the equivalent circuit. L is the inductance of the loop and $R = R_{loss} + R_{rad}$, the sum of the loss resistance and radiation resistance.

It is quite difficult to obtain the exact equivalent circuit values from the input impedance, particularly near resonance, and a more useful guide can often be obtained by consideration of the additional capacitance (C_T) required to cause the circuit to resonate. It is worth noting that the tuning capacitance necessary to obtain maximum voltage across the terminals under resonant

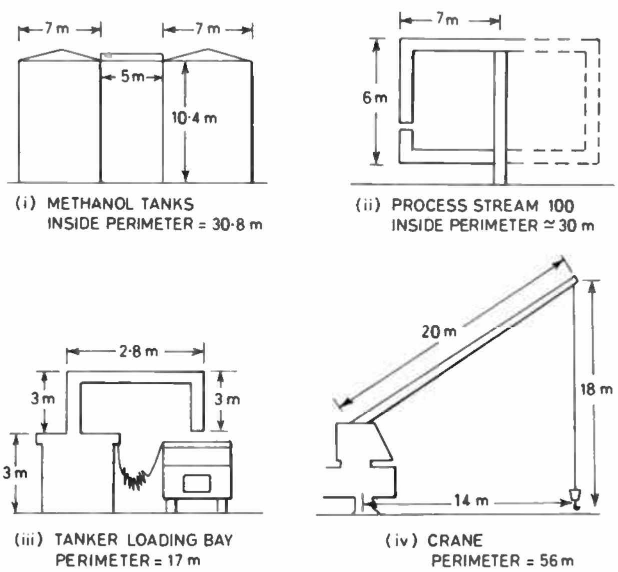


Fig. 2. Dimensions of some structures at St Fergus.

conditions will differ from the capacitance for current resonance if the resistance in the circuit is not insignificant compared with the reactance. The resistance (R) in the equivalent circuit is slightly more difficult to calculate, and many additional components may be necessary to obtain an equivalent which holds over a wide frequency range, particularly near self-resonance. Figure 2 shows diagrams of some of the more efficient structures examined on the three sites.

4.1.1 Methanol tanks (BGC)

Figure 3 shows the input impedance at the break between the walkway and the top of the tank of the Methanol Tanks on the BGC site. As an initial indication this corresponded quite well to an inductance of 7 μH with self and stray capacitance amounting to 350 pF. The structure appeared self-resonant at about 3 MHz with a maximum resistance of just less than 1000 Ω. Also shown in Fig. 3 is the variation of the apparent effective height with frequency. Since the effective height is calculated from the ratio of open-circuit voltage, which is greatest at the self-resonant frequency, to the field intensity, the effective height also maximizes at resonance. The three quantities, resistance, reactance and apparent effective height, are all that are required to characterize a structure, so that given the incident field intensity, reasonably accurate predictions of induced voltage and power can be made.

The equivalent circuits which have been developed may well hold for frequencies up to the first resonance, but it is difficult with a small number of lumped components to characterize the successive resonances of a large uniform loop. At this stage it is not known what

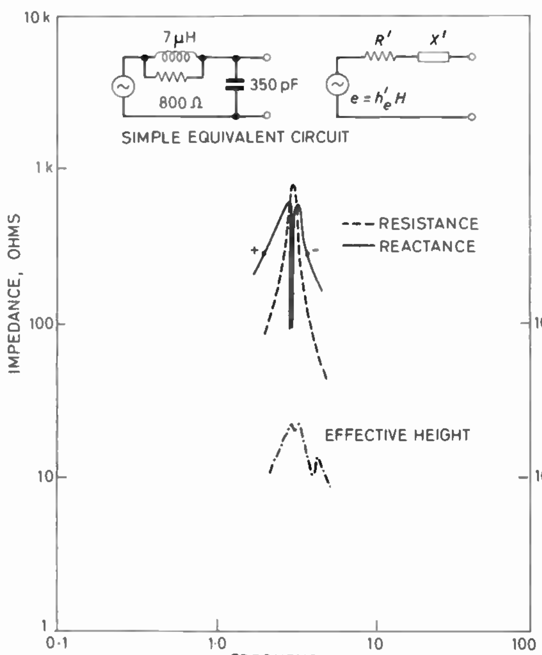


Fig. 3. Impedance of Methanol Tanks.

part the high frequency behaviour of the structure plays in the delivery of energy to a discharge.

4.1.2 Tanker loading bay (TOM)

The impedance curve of this structure (Fig. 4) was slightly more complicated than the previous structures in

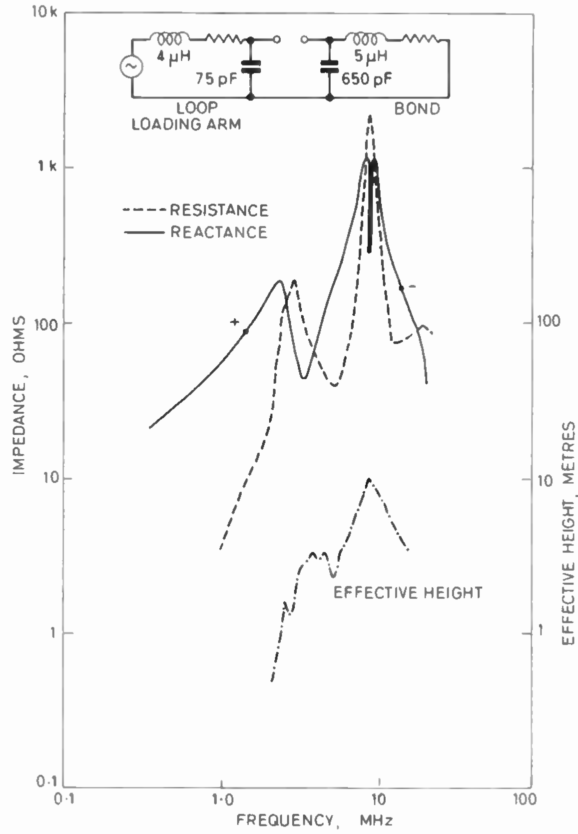


Fig. 4. Impedance of Tanker Loading Bay.

that a resonance was observed at 3 MHz in addition to the apparent major resonance at 9 MHz. This behaviour can be synthesized by the circuit shown, comprising two parallel tuned circuits. This would appear to have a direct interpretation relating directly to the structural configuration. The low-frequency resonance is associated with the inductance of the static bonds in parallel with the stray capacitance of the fire tender to ground. The main resonance at 9 MHz is probably associated with the impedance of the loop formed by the loading arm, where the perimeter of the loop approaches one half-wavelength.

This was a structure in which measurements were made at frequencies above 5 MHz, and the apparent effective height follows a dependence on frequency similar to that of the resistance in the circuit, maximizing at the resonant frequency 9 MHz. However no attempt was made to resonate the structure at these frequencies owing to the technical difficulties involved, and no measurements of induced power were made above 5 MHz.

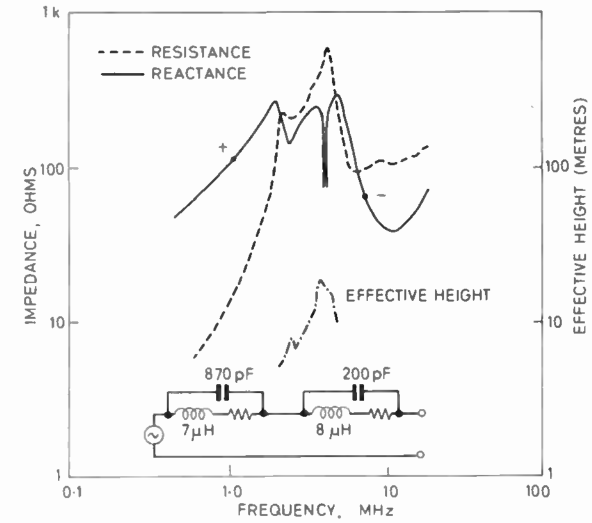


Fig. 5 Impedance of Process Stream 100.

4.1.3 Process streams 100 (TOM)

Measurements were made across the site of a removed valve. The impedance frequency characteristic for Process Stream 100 (Fig. 5) showed a similar characteristic to that of the Tanker Loading Bay and the equivalent circuit was consequently of similar nature. The main circuit resonance occurred at 4 MHz with a small resonance at about 2 MHz.

As with the previous structure the apparent effective height maximized at the frequency of the major resonance with a maximum value of about 20.

4.2 Vertical Structures

A preliminary analysis of vertical structures is given in Fig. 1, Item 2. The simple equivalent circuit (ii) shows the generator and source impedance of the base, which in all cases was concrete, to which a fairly low resistance can be attributed in addition to a large value of capacitance. The circuit is completed by the impedance of the earth lead, also with its own generator. At frequencies in the 2–20 MHz range the circuit reduces to that of (iii) where the impedance of the earth lead is the dominant feature and the system would require capacitance to tune the structure below the first resonance of the earth lead impedance.

4.2.1 Vent stack

Figure 6 shows the vent stack impedance/frequency characteristic which appears to be predominantly resistive over the frequency range 1–10 MHz. The analysis of this behaviour can be interpreted as the sum of the impedances of the two separate parts; the column and base impedance, and the earth lead impedance. However, to explain the low frequency behaviour some additional inductance across the base is required and this could be accounted for by the pipe which was attached to

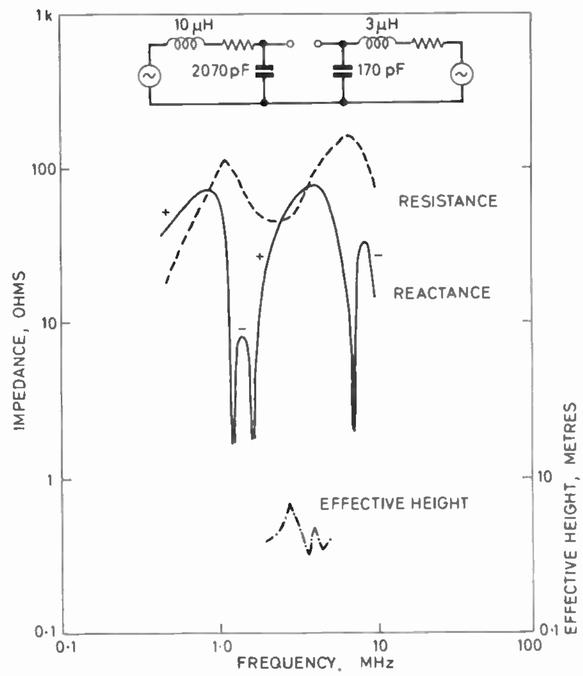


Fig. 6. Impedance of Vent Stack.

the stack and could not be removed for the tests. The apparent effective height was very low, probably due to the fact that voltage induced in the stack was highly attenuated by the base impedance.

4.3 Cranes

In all, three basic types of crane were tested, two telescopic types with 20 metre jibs and one 50 metre fixed jib crane. One of the 20 metre jib cranes was on the TOM site with a large 36 in. steel pipe to provide a conductor between the chassis of the crane and the point of measurement directly below the hook. The other 20 metre jib crane was tested on the Shell site and several configurations of jib length, elevation and orientation were examined. However for the bulk of the tests the jibs were at 45° elevation in the direction of Crimond. It was not possible to use the impedance meter on any of the cranes owing to the high level of induced voltage. The impedance results were obtained from the measurements of voltage and current although some measurements were made using BBC transmissions at frequencies below 2 MHz.

4.3.1 20 metre jib cranes

Figure 7 shows the impedance of the crane on the Shell site. The crane exhibited apparent self-resonance at about 2 MHz, which corresponded quite well to the expected resonant frequency for a $\lambda/2$ perimeter, which would be about 2·7 MHz. The crane on the TOM site had a very similar characteristic. Both the 20 metre cranes were tested with the jib at 45° elevation and measurements were made between the hook and an

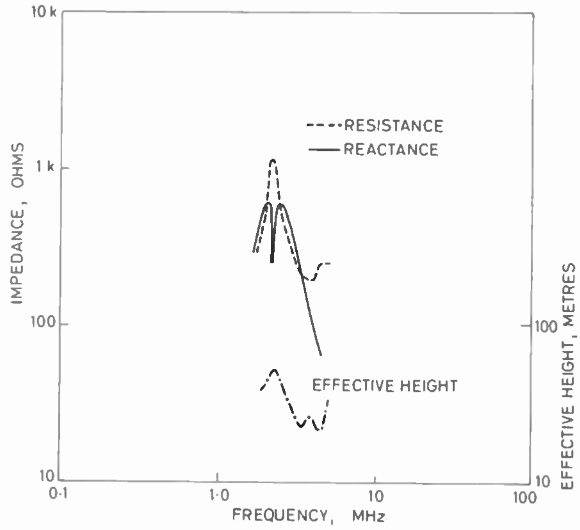


Fig. 7. Impedance of 20 m jib length crane.

earth-mat. However, the tests on the crane on the Shell site, which was situated in a relatively isolated area, indicated that the crane was not behaving as a loop type structure. The results of these measurements are summarized in Table 2, for nine 20 kW transmitters.

Table 2

Test	Jib Elevation Above Horizontal	Angle of Incidence with Crimond	Cumulative Open-Circuit Voltage
a	45°	0°	18 V
b	45°	90°	18 V
c	80°	90°	23 V

The change in orientation of the jib from 0° to the direction of Crimond (test a), i.e. the optimum configuration for reception of the magnetic component of transmitted field from Crimond, to 90° (test b), where coupling with the magnetic component should be minimal, resulted in no change in cumulative open-circuit voltage, indicating that interaction with the electric component was dominant for that particular

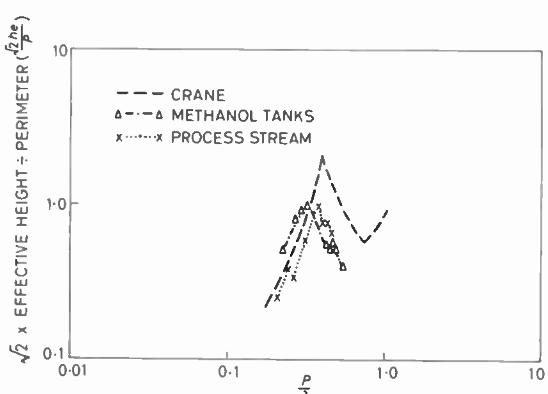


Fig. 8. Loop characteristics, normalized effective height.

configuration. Moreover, increasing the jib elevation to about 80° (test (c)) resulted in a further increase in voltage under conditions where the area of the loop was reduced.

Both cranes had apparent effective heights of about 50 metres at the self resonant frequency which was about 2·5 times higher than that of any fixed plant structure.

4.3.2 50 metre jib crane

This crane was tested in the folded monopole configuration with a very high jib elevation, the induced voltage being measured between the hook and the caterpillar track. The impedance of the crane indicated a series resonance, i.e. low impedance condition, at about 3 MHz. This corresponds well with the vertical height of 50 metres being $\lambda/2$ and a perimeter of approximately one wavelength.

The apparent effective height was at a minimum at 3 MHz also, and again indicated the relationship between this parameter and the impedance.

The cumulative open-circuit voltage measured on this crane was 3 V at transmitter powers of 2 kW, which would correspond to about 9·5 V for 20 kW transmissions. This should be compared with the 23 V measured on the 20 metre crane under a similar physical condition and indicates that size alone is not the overriding factor in the induction of high voltages and powers.

4.4 Further Analysis

For all the uniform structures examined it appeared that there was a relationship between the primary self-resonant frequency, where the effective height and the impedance achieved their maximum values, and the dimensions of the structure.

Figure 8 shows the effective height values normalized with respect to structure perimeter, expressed as a function of the perimeter to wavelength ratio. For the three most efficient structures found on the sites, the curves indicate that maximum effective height, and therefore maximum open-circuit voltage per unit field, was obtained when the perimeter of the structure was approximately $0{\cdot}4\lambda$. This is in agreement with established large loop theory.[7]

The efficiencies of the structures obtained by comparison of the available power (P_i) with the power (P_0) expected in a near-ideal lossless tuned aerial, are shown in Fig. 9 as a function of the perimeter to wavelength ratio (p/λ). The power in the near ideal aerial was calculated using the expression $P_0 = S\lambda^2/8{\cdot}4$ where S is the incident power density and λ the wavelength. For the three structures analysed the efficiency increased very rapidly at low values of p/λ up to a maximum value of $n = 0{\cdot}5$.

From this analysis it would appear possible that from a knowledge of structure dimensions, transmission frequency and incident field strength, the open-circuit

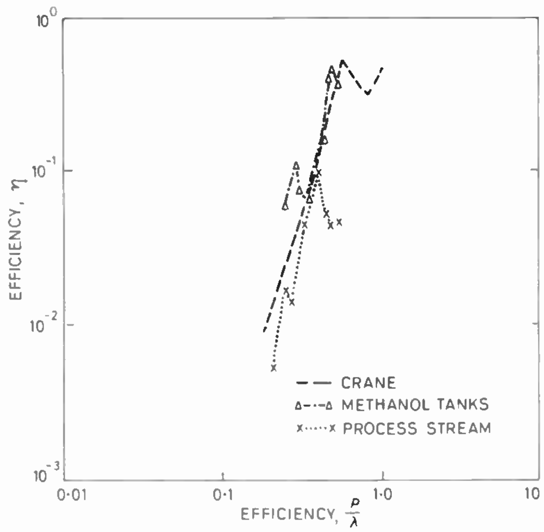


Fig. 9. Loop characteristics.

voltage and available power can be predicted. This power can be compared with the ignition threshold power for the gas or vapour likely to be found in the vicinity of the discontinuity in the structure, and an assessment of the potential hazard may be obtained.

5 Field Strength

5.1 Frequency range 2–5 MHz

Measurements of field intensity were made near each of the structures examined. The variations in field on the Total and BGC sites were quite large at several frequencies, apparently due to the re-radiation from currents induced in nearby structures, which could reinforce or reduce the incident field. A significant proportion of the field close to large structures may be due to the re-radiated field, the enhancements of 6 dB to 10 dB over the free space values were readily observed. However for the calculations of the efficiency it has been assumed that the induced voltage and power in the structure related to the incident radiation from the Crimond transmitters.

In order to assess the enhancement produced by a structure, field strength measurements were made with and without the presence of a 20 metre jib telescopic crane. The increases in field strength local to the crane were in the range 3 to 9 dB and indicated the contributions of the re-radiated field due to induced currents.

Similarly, screening by girder work can have a considerable effect; attenuations of between 12 and 21 dB were obtained by moving from a clear area to inside a girder complex on the Shell site.

5.2 Frequencies above 5 MHz

The measurements of field strength that were made at three frequencies in the 8–16 MHz frequency range with each transmitter operating at 20 kW are summarized in Table 3, with the field strength expressed in volts per metre.

Table 3

Test No.	Site	Frequency (MHz) 8·6	10·2	15·95
81	TOM	0·0016	0·0019	0·0009
82	TOM	0·0018	0·0022	0·0004
83	HO Site No. 8	0·0040	0·0063	0·0013

These values can be compared with the typical field strength values of 0·07 V/m which were measured on the BGC site at about the same time at frequencies below 5 MHz; the fields at these higher frequencies were considerably lower. These results are compatible with the high attenuations to ground wave propagation expected at similar distances at frequencies above 5 MHz, which are well documented in CCIR publications.[4] This effect indicates that transmissions from Crimond in the 5–30 MHz range would not produce field strengths at the St Fergus Gas Terminals comparable with those at lower frequencies, and therefore the frequency range of interest can be confined to the 2–5 MHz range.

5.3 Variations in Field Strength with Environmental Conditions

This subject is dealt with in some detail in Annex E of the Technical Sub-Committee Report.[5] It was found that the field strengths measured at the Home Office site No. 8 in January 1978[3] were higher than those obtained in October and November 1978, an effect which was apparently associated with changes in ground conductivity. In order to make predictions of the situation that could arise under the worst case ground conditions, some allowance for the changes was necessary; this was also based on CCIR data.[4] In

Table 4

	Frequency (MHz) 2·2	2·6	2·8	3·3	3·97	4·04	4·3	4·5	5·0
October 1978	+13	+5	+4	+5	+1	+17	+7	+7	+6
November 1978	+11	+4	+2	+3	+5	+5	+16	0	+4

addition, some estimate was necessary to account for the inefficiency of the aerials at Crimond working at frequencies below 3 MHz. The overall factors (in dB) which needed to be applied to the induced voltages and powers to account for efficient aerials and good ground conductivity are shown in Table 4.

Allowance for the apparent gains of the log periodic aerials was also made, effectively referring all transmissions to equivalent omnidirectional aerials.

6 Prediction of the Potential Hazard Situation

A prediction of the potential hazard was made for 13 transmissions at 20 kW each, five at about 2 MHz and eight at about 4 MHz. A further case of sixteen transmitters, where another three transmitters on about 3 MHz were included, was also assessed. The factors considered in Section 5.2 were applied to the induced voltages and powers for the condition when the structure was resonated to obtain maximum voltage. Table 5 indicates the voltages and powers predicted[8] for the most efficient fixed structure, the Methanol Tanks, and also a 20 metre crane.

Table 5

Structure	13 Transmitters		16 Transmitters	
	Voltage (peak)	Power (watts)	Voltage (peak)	Power (watts)
Methanol Tanks	49	0·42	53	0·43
Crane	142	1·32	176	1·54

The maximum power predicted was 1·54 watts, which is considerably less than the power required for the ignition of methane gas, and a healthy safety margin was demonstrated. A more realistic assessment of the 16 transmitter situation, where the frequency separation and gas ignition times were taken into consideration, yielded even lower powers than those presented in the Table, namely 0·056 W for the Methanol Tanks and 0·31 W for the crane. The contributions of the l.f. transmissions were found to be insignificant.

7 Conclusions

1. A vast amount of data was accumulated on a large number of specially selected structures, and provided a high degree of confidence in the evaluation of the characteristics of structures on gas plant in extracting energy from an incident electromagnetic field.

2. The voltages and powers measured in the structures for nine transmitters at 20 kW operating on a pattern spread across the 2–5 MHz range were fairly low, the maximum voltage measured was 36 volts peak for an externally resonated crane structure. These levels failed to ignite hydrogen gas in the IEC breakflash apparatus.

3. The cumulative open-circuit induced voltage at a number of frequencies was found to be very close to the sum of the voltages at the individual frequencies. The envelope of the cumulative signal waveform was found to be fairly uniform with the average value not too far below the sharp peak. In most cases artificially resonating the structure resulted in an increase in cumulative voltage of less than 50%.

4. Many of the structures exhibited a high impedance resonance where the structure appeared to be marginally more efficient. It was possible to develop relatively simple equivalent circuits which characterized the structure up to the first major resonance.

5. Large isolated loop structures were found to be the most efficient types and cranes in particular gave the highest induced voltages and powers. Vertical structures were found to be much less efficient, apparently due to the low r.f. impedance associated with the concrete base. Only six of the fixed structures, i.e. excluding cranes, had efficiencies greater than 1%, and only two of these had efficiencies which exceeded 10%.

6. The efficiencies of uniform structures were found to be closely related to the structure dimensions and the values of transmission frequency and field strength could be applied to provide a reasonably accurate assessment of the potential hazard due to single frequency sources.

7. The field strength was found to vary considerably around the plants but there was no strong evidence to suggest that enhancement played a major role in producing increased voltages and powers in a structure.

8. The prediction of the maximum available power in a structure for a worst-case grouping of 16 transmitters operating at 20 kW each was 1·54 W which is considerably less than the ignition power threshold of methane. Even lower figures would be obtained if a more realistic approach was taken.

8 References

1 Report of the Steering Committee on radio frequency ignition hazards at St Fergus, Scotland. Published by Health and Safety Executive.
2 ERA Report No. 3477/1. 'Test Results. Investigation into the interaction of structures at the St Fergus gas terminals with radio frequency transmissions from RN Crimond'.
3 Home Office Report No. RT/RIB/78.
4 CCIR Recommendations 368-2.
5 Report of the Technical Sub-Committees of the Steering Committee for further investigation at RN Crimond/St Fergus, Scotland. DOC SC 60.
6 Knight, P., 'Radio Frequency Ignition Hazards. The effect of the ground on the resistance of a loop antenna'. BBC Research Department Report.
7 Storer, J. E., 'Impedance of thin wire loop antennas', *Trans. Am. Inst. Elect. Engrs (Communications and Electronics)*, 75, pt. 1, pp. 606 19, November 1956.
8 ERA Report No. 3477/2 'Analysis of results of measurements of induced r.f. voltage and power at the St Fergus Gas Terminal'.

Manuscript first received by the Institution on 10th September 1980 and in final form on 2nd February 1981
(Paper No. 1980/M119)

UDC 621.372.57
Indexing Terms: Electric filters, active

Group delay sensitivity—its estimation and application

SHYAMA CHARAN PRASAD, M.Sc., Ph.D.*

and

RAM PUKAR SINGH, M.Sc.†

SUMMARY

The output of a filter network gets distorted due to changes in the level of the group delay of its transfer function and group delay sensitivity could, accordingly, serve as an index of such distortions. A formulation relating the group delay sensitivity to polynomial coefficient sensitivity, which enables a quick evaluation of the former, is proposed and its use as a selection criterion is illustrated with the active RC network synthesis of a second-order low-pass Bessel filter.

* *Department of Physics, Langat Singh College, University of Bihar, Muzaffarpur 842 001, India.*
† *Department of Physics, Rameshwar Singh College, University of Bihar, Muzaffarpur 842 001, India.*

The Radio and Electronic Engineer, Vol. 51, No. 4, pp. 195–197, April 1981

1 Introduction

Group delay (τ) is an important characteristic of the voltage transfer function of a network excited by sinusoidal signals. Given by a rational function in the signal frequency (ω), it is always finite and variations in its value imply the introduction of distortion by the network during signal processing.[1] To eliminate such distortions, sometimes a transfer function having a constant group delay over the frequency band of interest is employed, e.g. a Bessel polynomial which approximates a low-pass transfer function having a maximally-flat group delay. However the transfer function and consequently the group delay of the network realizing such a prescribed characteristic may differ from their stipulated values due to perturbations in the values of circuit elements. This will lead to distorted output unless the circuit elements are so chosen that changes in the value of group delay due to possible variations in the values of circuit elements are constant over the frequency band of interest, i.e. the sensitivity of the group delay with respect to circuit elements should either be zero or constant over the required frequency range. A study of the group delay sensitivity may therefore be useful during the synthesis of a filter network satisfying a prescribed characteristic function. A method based on the adjoint network concept has recently been described[2] for the evaluation of group delay sensitivity and an alternative method based on the polynomial coefficient sensitivities is being proposed in this paper. The formulation enables a quick evaluation of the group delay sensitivity over a band of frequencies. Its utility in the design of filter networks has been illustrated by a discussion of active RC network realization of low-pass Bessel polynomial of the second order.

2 Group Delay Sensitivity

If $H(s)$, a rational function in complex frequency s ($=j\omega$) be the voltage transfer function of a network and its poles and zeroes be p_i and z_r ($i = 1, 2, \ldots n$; $r = 1, 2, \ldots m$) then one can write

$$H(s) = \frac{\sum_{i=0}^{m} a_i s^i}{\sum_{i=0}^{n} b_i s^i} = \frac{\prod_{r=1}^{m} (s+z_r)}{\prod_{i=1}^{n} (s+p_i)} \quad (1)$$

The group delay τ of $H(s)$ is now given by

$$\tau = \sum_{r=1}^{m} \frac{z_r}{\omega^2+z_r^2} - \sum_{i=1}^{n} \frac{p_i}{\omega^2+p_i^2} \quad (2)$$

Sensitivity of the group delay with respect to a parameter of interest x, S_x^τ may be defined as

$$S_x^\tau \triangleq x\frac{\partial\tau}{\partial x} \quad (3)$$

Using relation (2), the following expression is obtained for S_x^τ:

0033-7722/81/040195+03 $1.50/0

$$S_x^{\tau} = \sum_{r=1}^{m} \frac{\omega^2 - z_r^2}{(\omega^2+z_r^2)^2} z_r S_x^{z_i} - \sum_{i=1}^{n} \frac{\omega^2 - p_i^2}{(\omega^2+p_i^2)^2} p_i S_x^{p_i} \quad (4)$$

with

$$S_x^{r_i} = \frac{x}{r_i}\frac{\partial r_i}{\partial x}$$

being the root $(=r_i)$ sensitivity.

Now with the use of expressions for root sensitivity due to Dutta Roy and Bhargava,[3] relation (4) modifies to

$$S_x^{\tau} = \sum_{i=1}^{n} \frac{\omega^2 - p_i^2}{(\omega^2+p_i^2)^2} p_i \frac{\sum_{l=0}^{n} b_l p_i^l S_x^{b_l}}{\sum_{l=0}^{n} l b_l p_i^l} - \sum_{r=1}^{m} \frac{\omega^2 - z_r^2}{(\omega^2+z_r^2)^2} z_r \frac{\sum_{l=0}^{m} a_l z_r^l S_x^{a_l}}{\sum_{l=0}^{m} l a_l z_r^l} \quad (5)$$

where

$$S_x^{a_l(b_l)} = \frac{x}{a_l(b_l)}\frac{\partial a_l(b_l)}{\partial x}$$

is the polynomial coefficient sensitivity.

The polynomial roots p_i and z_r, if complex, occur in complex conjugate pairs so that the terms on the r.h.s. of relation (5) will also contain complex conjugate pair terms and S_x^{τ} will be real.

As the expression (5) shows, S_x^{τ} depends upon frequency (ω) and is always finite. Since a variation in the value of group delay leads to distortion, the element values of the filter network must be chosen such that the group delay sensitivity is not only low but constant over the frequency band of interest.

3 Illustration

Consider the realization of a second-order low-pass Bessel polynomial which approximates a maximally-flat group delay function by an active RC network (Fig. 1) In this case the various polynomial coefficients are

$$n = 2, \quad m = 0;$$
$$a_2 = 0, \quad a_1 = 0, \quad a_0 = 1;$$
$$b_2 = 1, \quad b_1 = 3, \quad b_0 = 3.$$

Using unit valued capacitors, a number of possible sets of values of resistors R_1 and R_2 may be obtained for

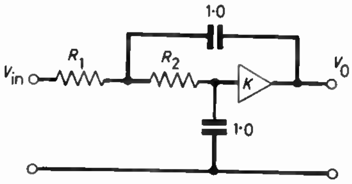


Fig. 1. A second-order active RC network.

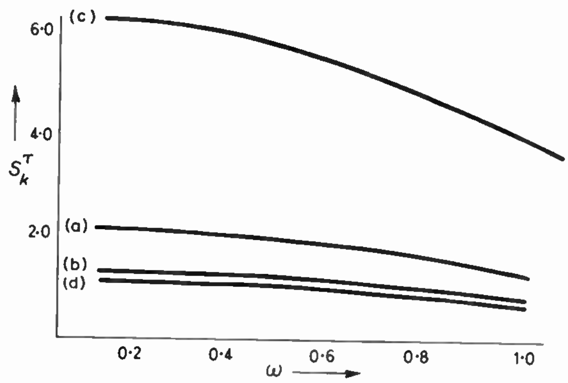


Fig. 2. Sensitivity characteristics.
(a) $K = 1{\cdot}3$, resistance spread $= 2{\cdot}42$.
(b) $K = 1{\cdot}3$, resistance spread $= 1{\cdot}18$.
(c) $K = 1{\cdot}6$, resistance spread $= 13{\cdot}3$.
(d) $K = 1{\cdot}6$, resistance spread $= 2{\cdot}1$.

various values of gain K. Selecting K as the critical element, the group delay sensitivity has been evaluated for various possible solutions over the frequency range $0{\cdot}1 \leqslant \omega \leqslant 1{\cdot}0$. For a value of K in the range $1{\cdot}25 \leqslant K < 2{\cdot}0$ two possible solutions for R_1 and R_2 exist and it has been found that out of these, the one having greater resistance spread has poorer sensitivity characteristics (Fig. 2). Further a study of the difference

$$\Delta S = ([S_K^{\tau}]_{\omega=0\cdot1} \sim [S_K^{\tau}]_{\omega=1\cdot0})$$

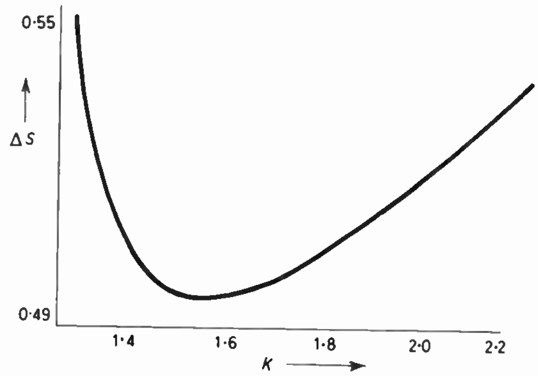


Fig. 3. Sensitivity variation—Gain curve.

for the possible solutions having lower resistance spread for K in the range $1{\cdot}3 \leqslant K \leqslant 2{\cdot}2$ (Fig. 3) shows that it is least for a value of K in the range $1{\cdot}5$, the resistance spread being in the range $1{\cdot}9$. Hence the gain and the resistance spread should be fixed in these ranges so as to minimize the effect of possible variation in the gain of the amplifier on the group delay of the network.

4 Conclusion

The group delay sensitivity of a network, a function of signal frequency, is always finite and real so that the group delay tends to change from its stipulated value due to possible variation in the value of network elements.

Such a variation in the level of the group delay will distort the signal beyond the permissible limits. In the design of active RC networks there is always a wide choice over the selection of the values of various elements of the network satisfying a prescribed characteristic function, hence a study of the group delay sensitivity may be useful in selecting a set of element values which ensures a uniform value for the former. For a quick evaluation, the group delay sensitivity has been expressed in terms of the polynomial coefficient sensititivty and its use as a selection criterion during the design of active RC network has been illustrated with the synthesis of a second-order low-pass Bessel polynomial.

5 References

1 Budak, A., 'Passive and Active Network Analysis and Synthesis', p. 496 (Houghton Mifflin, Boston, 1974).

2 Temes, G. C. and LaPatra, J. W., 'Introduction to Circuit Synthesis and Design', p. 426 (McGraw-Hill, New York, 1977).

3 Dutta Roy, S. C. and Bhargava, D. K., 'Sensitivity of third and higher order filters', *Intl J. Circuit Theory and Applications*, **5**, no. 3, pp. 235–8, 1977.

Manuscript received by the Institution on 4th March 1980.
(Paper No. 1982/CC 334)

The Vivaldi Aerial

An aerial having a gain of about 10 dBI with associated sidelobe level of −20 dB over an instantaneous frequency bandwidth extending from 2 GHz to 40 GHz has been devised at the Philips Research Laboratories, Redhill.

Radiation from microstrip structures on substrates of high dielectric constant is low, making it difficult to integrate aerials and front end circuits on the same substrate. One solution to this, for applications up to 3% bandwidth, has been the use of resonant slot-line radiator arrays. Slot-line, under matched termination conditions, does not radiate significantly and slot-line techniques for microwave circuit designs have been extensively used at the Philips Laboratories. The new aerial, the Vivaldi aerial, exploits a further property of slot-line when the slot extends to regions where the edge separation is greater than $\lambda/2$.

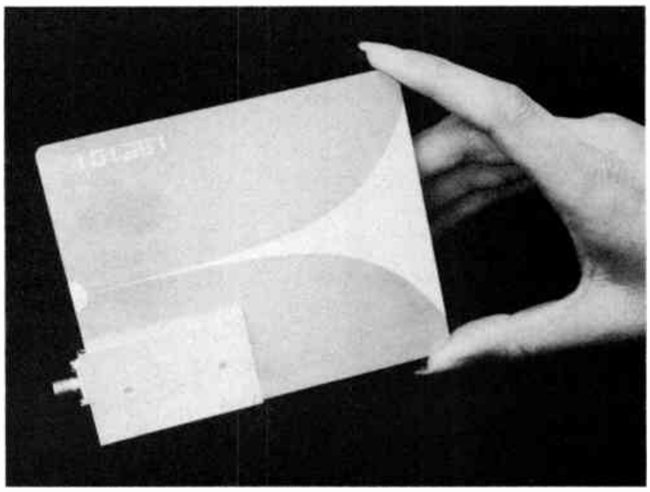


Fig. 2. An 8 40 GHz microwave 'Vivaldi' aerial printed on the same substrate as the video receiver circuit.

When the separation is small compared with the free space wavelength, the energy in the travelling wave is tightly bound to the conductors but becomes progressively weaker and more coupled to the radiation field as the separation is increased. For principal mode operation the phase velocity of the bounce wave on the conductors must equal or exceed that in the surrounding medium. This demands continuous phase-leading compensation which is accomplished mainly by the substrate material; such aerials can provide frequency bandwidths of about 6:1 but, for more extended bandwidths, additional phase compensation is required.

The Vivaldi has an end-fire characteristic and the beamwidth is about the same in E and H planes; the gain is proportional to the overall length and also to the mode-coupling profile. The aerial is constructed by normal microwave photolithographic thin film techniques on a high dielectric constant substrate; other circuit elements can be printed on the same substrate to form a complete very wideband receiver head.

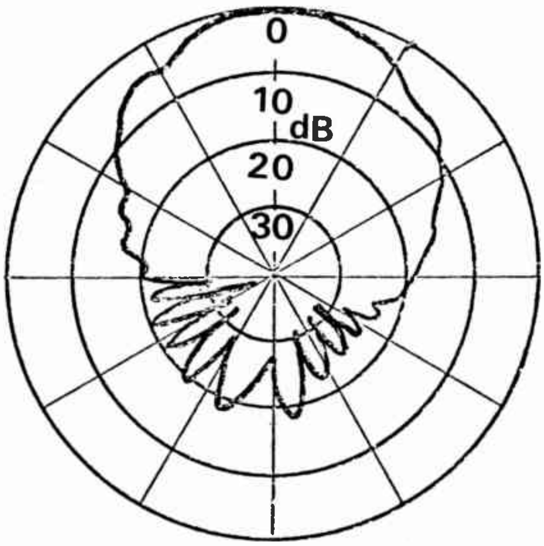


Fig. 1. Radiation diagram.

Contributors to this issue

Professor David Howson (Fellow 1969, Member 1961) took his B.Sc. degree at Bristol University in 1952. He then spent five years in industry as a design engineer with Standard Telephones & Cables before taking his M.Sc. in information engineering at Birmingham University. From 1958 to 1967 he was successively Lecturer and Senior Lecturer at Birmingham University. In 1968 he was appointed to his present position as Professor of Electrical and Electronic Engineering at the University of Bradford, having obtained his D.Sc. from the University of Birmingham in the same year. He is the co-author of three books and author or co-author of many papers and articles on various aspects of communications engineering, in which field lie his current research interests.

Peter Excell received the B.Sc. degree in engineering science from the University of Reading in 1970. He worked for six months as a Graduate Assistant at the University of Ife, Nigeria, and returned to the UK to take up a post as an Experimental Officer at the University of Bradford in 1971 where his early work was in the field of power electronics. In 1974 his post was changed to that of Research Assistant and he commenced work in ignition hazards of electromagnetic radiation. In 1978 he was promoted to Research Fellow, working on a study of near-field effects in an electromagnetic susceptibility test range. In 1979 he was made a lecturer and in 1980 was awarded the Ph.D. degree by the University of Bradford for research in radio frequency ignition hazards. He has acted as consultant on r.f. hazards to several oil-related companies and has been a member of a number of national committees on this problem.

George Butcher was awarded the Higher National Certificate in electrical engineering by Bradford Technical College in 1955, while serving an industrial apprenticeship. After service in the Royal Air Force he joined the UK Atomic Energy Authority as an Assistant Experimental Officer and worked on the Dounreay Fast Breeder Reactor Project for 1½ years until the end of 1960. He then took up a post as a Senior Technician at Leeds University, working on a cosmic ray detector array. In 1964 he moved to his present post of Experimental Officer at the University of Bradford where his main research activities have concerned acoustic anechoic chambers, linear induction motors and induced ignition hazards due to radio-frequency radiation. He was awarded the M.Sc. degree by the University of Bradford in 1979 for research in radio-frequency ignition hazards.

Gerry Jackson (Fellow 1978) graduated with a London University external honours degree in physics in 1945 following study at University College, Exeter. After six years in industry he joined ERA in 1952 and has worked on problems in electromagnetic interference including techniques of measurement, instrumentation and screening. He is now Manager of the Electromagnetic Interference Department and is internationally involved as a Vice Chairman of the International Special Committee on Radio Interference and Chairman of CISPR SCB (ISM equipment). He has served on Organizing Committees for IERE conferences on Electromagnetic Compatibility, being chairman for the 1980 and 1982 events.

Tony Maddocks joined the Electromagnetic Interference Department at ERA Technology in 1969 after three years in industry working on the hazards associated with the use of electro-explosive devices in radio frequency fields. His work at ERA has been primarily concerned with investigations into the problems associated with electromagnetic compatibility in the industrial, domestic and commercial environments, and he has contributed to a number of research projects in this field. In recent years his work has also included investigations into the radio frequency spark ignition hazard and he has been involved in a number of practical hazard assessments on gas and petrochemical plants.

Ram Pukar Singh received his B.Sc. and M.Sc. in physics with specialization in spectroscopy from Langat Singh College, University of Bihar Muzaffarpur in 1962 and 1964 respectively. He joined Rameshwar Singh College, Muzaffarpur, in 1965 as lecturer and is now head of the department of physics. He is pursuing research work in the field of circuit theory.

Shyama Charan Prasad studied at L.S. College, University of Bihar, Muzaffarpur, for his B.Sc., M.Sc. and Ph.D. degrees in physics which he received in 1962, 1964 and 1976 respectively. He joined Bhagalpur University as a Lecturer in July 1966 and was appointed a Lecturer in Physics at L.S. College in 1967. From 1976 to 1978 he held a Post Doctoral Fellowship in the Electrical Engineering Department, Indian Institute of Technology, New Delhi. Dr Prasad's main research fields are network theory and filter design. One of his previous papers in the field of present paper (with Dr D. K. Jha) was awarded the Sir J. C. Bose Premium for 1976.