NOTICE OF THE THIRTY-SIXTH ANNUAL GENERAL MEETING

NOTICE IS HEREBY GIVEN that the THIRTY-SIXTH ANNUAL GENERAL MEETING (being the twenty-eighth since Incorporation under the Companies Acts 1929 and 1948) of the Institution will be held on WEDNESDAY, 24th JANUARY 1962, at 5.30 p.m. at the London School of Hygiene and Tropical Medicine, Keppel Street, Gower Street, London, W.C.1.

AGENDA

1. **To confirm the Minutes of the 35th Annual General Meeting held on 11th January 1961.**
   (Reported on pages 190–192 of Volume 21 of the *Journal* dated February 1961.)

2. **To receive the Annual Report of the Council for the Year ended 31st March 1961.**
   (A copy of the Report is being sent separately to all Corporate Members.)

3. **To receive the Auditors' Report, Accounts and Balance Sheets for the year ended 31st March 1961.**
   (The Auditors' Report, Accounts and Balance Sheets are given on pages 450–452 of this issue of the *Journal*.)

4. **To express thanks to the Institution's Solicitors, Braund and Hill, 6 Gray's Inn Square, London, W.C.1.**

5. **To express thanks to the Institution's Auditors, Gladstone, Jenkins & Co., 42 Bedford Avenue, London, W.C.1.**

6. **Awards to Premium and Prize Winners.**
   (Details of Premium Awards were given on page 178 of the *Journal* dated September 1961.)

7. **Any other business.**
   Notices of any other business must reach the Secretary 40 days before the meeting.

This Agenda does not provide for the customary election of President, Vice-Presidents, ordinary members of Council and the Honorary Treasurer, as the Charter of Incorporation names the holders of these offices.

A Special General Meeting of Corporate Members will be convened later in order to approve Bye-Laws for the Institution under its Charter. (See *Journal* for August 1961, page 82.)

35th Annual Report of the Council of the Institution

As a body incorporated on 8th August 1932 under the Companies Act, 1928, 1949, the Institution is holding its last Annual General Meeting on 24th January 1962. The Agenda for this 36th and last Annual General Meeting of the incorporated body is published on page 449 of this *Journal*.

The January 1962 *Journal* will contain the full Annual Report of the retiring Council in the same detail as has been presented to members since 1944. The Report marks an important stage in the history of the Institution* and its transition from a small organization founded at its first meeting held on 31st October 1925, steadily growing to justify incorporation in 1932 and finally achieving almost thirty-six years later the honour and dignity of a Royal Charter of Incorporation.

The forthcoming Annual General Meeting is, therefore, the final meeting of corporate members of the body incorporated in 1932. The Accounts and Report provide, therefore, a comprehensive statement of the assets and liabilities and the general position of the British Institution of Radio Engineers as an incorporated body and referred to in the Charter of 2nd August 1961 as "... the existing Association". Article 22 of the Charter also provides that:

> "The property and moneys of the existing Association shall from the date of these Presents become and be deemed to be the property and moneys of the Institution, and shall, as soon as may be, be formally transferred to the Institution or such person or persons on its behalf as the Bye-laws may prescribe."

Members of the Institution who were the Petitioners for the grant of a Charter (as stated in *J.Brit.I.R.E.* August 1961, page 82) are at present drafting the Bye-laws of the Institution and these will make provision for the conduct of the Institution, including the holding of Annual General Meetings. In this latter connection, the Bye-laws will provide for the Institution's financial year to be the same as before the granting of a Charter, i.e. 1st April to the succeeding 31st March. Thus the first annual report and accounts of the Chartered Institution will cover the period 1st April 1961 to 31st March 1962 and will be presented to corporate members at an Annual General Meeting toward the end of 1962. It is hoped to lay the draft Bye-laws before members at a Special General Meeting to be convened during the early part of 1962.

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* Further information on how the Institution was formed and its subsequent history is given in "A 20th Century Professional Institution" published by the Institution, price 30s. post free.

Corporate members will, therefore, on 24th January next, be marking the end of an era in the history of the Institution. The assets and liabilities taken over by the Chartered Institution are shown in the Balance Sheet given on page 452 of this *Journal* and the Schedule of Investments referred to therein are given below.

In a recent editorial an Officer of the Institution stated that the next most important step in the history of the Brit.I.R.E. must be the acquisition of a larger building. The Schedule of Investments and the Balance Sheet published on page 452 indicate that substantial progress has been made in accumulating funds for the purchase of suitable and adequate Institution headquarters.

Investments at Cost, 31st March, 1961

SCHEDULE (1)—GENERAL FUND		£	s.	d.
£200	3% Savings Bonds 1960/70	200	0	0
£600	4% British Transport	544	1	4
£800	4% Consolidated Stock	712	15	6
£1,000	5½% Commonwealth of Australia 1977/80	987	13	7
£200	Ether Langham Thompson — 800			
	Ordinary Shares of 5/– each ..	(*Donated*)		
	(Market Value as at 31st March, 1961 £2,522 10s.)	£2,444	10	5

SCHEDULE (2)—BUILDING APPEAL				
£2,000	3½% War Loan	1,464	4	3
£1,400	4% Consolidated Stock	1,219	3	0
£3,000	4% British Transport 1972/77 ..	2,754	9	5
£1,300	3% British Electricity 1968/73 ..	990	10	6
£1,500	3% Exchequer Stock 1962/63 ..	1,428	10	7
£1,200	5% Conversion Stock 1971 ..	1,186	18	3
1,600	Orthodox Unit Trust Limited ..	1,032	8	6
£1,000	6% Federation of Rhodesia & Nyasaland 1978/81	988	0	1
250	A.E.G. Unit Trust Limited	145	0	6
£500	5½% Commonwealth of Australia ..	492	11	7
2,000	Falcon Trust Limited	500	0	0
£500	Imperial Chemical Industries— 5% Preference Shares	452	19	6
200	Commonwealth Trust	100	0	0
£500	National Commercial Bank of Scotland	1,425	6	0
£500	British Petroleum 8% Preference Shares	684	12	9
£100	6% Associated Electrical Industries Limited Debenture Stock 1978/83	98	10	0
£500	Hawker Siddeley Ltd. Ordinary Shares	746	4	6
£500	South Durham Steel Iron Ltd. Ordinary Shares	1,040	5	1
£200	Shell Transport Ltd. £1 Reg. Stock	1,632	5	6
£50	City of Birmingham 6% Loan (Call)	50	0	0
(Market Value as at 31st March, 1961 £16,755 10s.)		18,432	0	0
	Halifax Building Society Deposit ..	5,000	0	0
	Cash at Bank	6,106	12	11
		£29,538	12	11

THE BRITISH INSTITUTION OF RADIO ENGINEERS

GENERAL ACCOUNT

INCOME AND EXPENDITURE ACCOUNT FOR THE YEAR ENDED 31st MARCH, 1961

1960 £	£		£ s. d.	£ s. d.
		ADMINISTRATION EXPENSES:		
	13,206	*Salaries and State Insurance* ..	.. 14,490 7 3	
	860	*Pension Scheme*..	.. 1,222 11 7	
	1,834	*Postage and Telephone*	.. 2,286 18 3	
	1,084	*Printing and Stationery* ..	.. 1,756 0 10	
	1,136	*Travelling and Entertaining Expenses*..	1,379 16 10	
	420	*Delegates Expenses*	.. 404 3 8	
	827	*Council and Committee Expenses* ..	832 14 6	
	150	*Audit Fees*	.. 210 0 0	
	464	*Bank Interest and Charges* ..	.. 853 7 0	
	220	*Legal and Charter Expenses* ..	.. 2,043 0 9	
	260	*Sundry Expenses*	.. 274 7 0	
20,461				25,753 7 8
		INSTITUTION'S PREMISES:		
	1,504	*Rent, Rates and Insurance (Net)* ..	1,559 7 3	
	447	*Lighting and Heating*	.. 618 4 5	
	843	*Office Expenses and Cleaning* ..	.. 991 6 1	
	364	*Repairs*	.. 46 19 2	
3,158				3,215 16 11
		INSTITUTION'S JOURNAL, LIST OF MEMBERS, LIBRARY, HISTORY AND OTHER REPORTS (NET):		
	9,808	*Printing and Publishing less Advertising*		
		Receipts	.. 10,709 1 3	
	1,920	*Postage*	.. 2,685 11 6	
	97	*Envelopes and Wrappers* ..	.. 269 11 2	
11,825				13,664 3 11
535		CONVENTION AND DINNER EXPENSES (NET)		— — —
		EXAMINATION EXPENSES:		
	450	*Printing of Papers and Regulations* ..	563 12 3	
		Examiners' and Invigilators' Fees and		
	589	*Expenses*	.. 420 10 11	
	143	*Hire of Accommodation* ..	.. 139 18 0	
1,182				1,124 1 2
		SECTION EXPENSES:		
	433	*Printing, Stationery and Postage* ..	522 5 9	
	833	*Hire of Accommodation, etc.* ..	.. 1,204 18 0	
	1,006	*Travelling Expenses and Subsistence* ..	1,108 9 10	
2,272				2,835 13 7
363		GRANTS TO OTHER INSTITUTIONS ..		415 18 3
170		PREMIUMS AND AWARDS	..	157 2 10
		DEPRECIATION:		
	381	*Office Furniture and Fittings* ..	.. 425 9 3	
	156	*Library*	.. 176 4 4	
537				601 13 7
40,503				47,767 17 11
		Excess of Income over Expenditure		
5,485		carried to Reserve Account		1,436 14 1
£45,988				£49,204 12 0

1960 £		£ s. d.
24,588	Subscriptions including arrears received	.. 27,050 4 3
5,380	Building Appeal Donations	.. 4,529 11 4
2,068	Donations from Industry	.. 1,504 18 11
2,540	Examination and Exemption Fees..	.. 3,401 5 1
1,784	Entrance and Transfer Fees	.. 2,166 7 6
5,772	Sales of Publications, etc.	.. 6,227 3 8
564	Interest on Investments (Gross)	.. 825 1 3
3,292	Radio Trades Examination Board: Secretarial Charges	.. 3,500 0 0
£45,988		£49,204 12 0

THE BRITISH INSTITUTION OF RADIO ENGINEERS

GENERAL ACCOUNT

BALANCE SHEET AS AT 31st MARCH, 1961

1960 £	£		£ s. d.	£ s. d.
		RESERVE ACCOUNT:		
		Excess of Income over Expenditure:		
		Balance at 1st April 1960 .. .. 13,863 16 6		
13,864		Add Surplus for the Year 1,436 14 1		15,300 10 7
		CURRENT LIABILITIES:		
	8,298	Sundry Creditors 7,650 0 7		
		Subscriptions and Examination Fees		
	6,420	in Advance 4,945 9 8		
	15,080	Bank Overdraft.. .. .. .. 23,192 1 5		
29,798				35,787 11 8
		Note: Expenditure of some Overseas Sections has been estimated where the audited accounts have not been received.		
£43,662				£51,088 2 3

1960 £	£		£ s. d.	£ s. d.
		FIXED ASSETS:		
		Office Furniture and Fittings at Cost.. 8,123 15 1		
3,421		Less Depreciation to date 4,291 15 1		3,832 0 0
		The Louis Sterling Library at Cost .. 2,818 8 10		
1,412		Less Depreciation to date 1,227 8 10		1,591 0 0
		INVESTMENTS AT COST:		
2,445		See Schedule (1) attached		2,444 10 5
		BUILDING APPEAL:		
25,368		See Schedule (2) attached		29,538 12 11
32,646				37,406 3 4
		CURRENT ASSETS:		
		Stock of Stationery, Journals and		
	4,441	Examination Papers at Valuation .. 5,812 11 2		
	532	Income Tax Repayment Claim .. 857 3 11		
	3,418	Sundry Debtors 4,416 19 1		
		Sections—Balances at Bank and in		
	96	Hand 105 16 8		
	2,515	Balances at Banks Overseas 2,453 2 5		
	14	Cash in Hand 36 5 8		
11,016				13,681 18 11
£43,662				£51,088 2 3

Signed: J. L. THOMPSON (*Chairman of Finance Committee*).
G. A. MARRIOTT (*Immediate Past President*).
G. A. TAYLOR (*Honorary Treasurer*).
G. D. CLIFFORD (*General Secretary*).

Brit.I.R.E. BENEVOLENT FUND

NOTICE OF ANNUAL GENERAL MEETING OF SUBSCRIBERS

NOTICE IS HEREBY GIVEN that in accordance with the Rules the Annual General Meeting of Subscribers to the Institution's Benevolent Fund will be held on WEDNESDAY, 24th JANUARY 1962, at the London School of Hygiene and Tropical Medicine, Keppel Street, Gower Street, London, W.C.1. The meeting will commence at 6.30 p.m. approximately (immediately after the Annual General Meeting of the Institution).

AGENDA

1. To confirm the Minutes of the Annual General Meeting of Subscribers held on 11th January 1961. (Reported on page 202, Volume 21 of the *Journal*, March 1961.)

2. To receive the Annual Report of the Trustees. (Published on pages 454–6 of this *Journal*.)

3. To receive the Income and Expenditure Account and Balance Sheet of the Benevolent Fund for the year ended 31st March 1961. (Published on page 456.)

4. To elect the Trustees for the year 1962.

   Rules 5 and 6 state:

   5. The Trustees of the Fund shall consist of not more than five and not less than three members of the Institution who have been elected at an Annual General Meeting of Subscribers to the Benevolent Fund.

   6. The Trustees shall be elected at the Annual General Meeting by all members who have subscribed to the Fund during the preceding twelve months, ended March 31st in each year, and the Trustees shall hold office until successors are appointed.

   The retiring Trustees are:

   Professor E. E. Zepler, Ph.D. (*Immediate Past President*)

   G. A. Marriott, B.A. (*Past President*)

   Rear Admiral Sir Philip Clarke, K.B.E., C.B., D.S.O. (*Past President*)

   Air Vice Marshal C. P. Brown, C.B., C.B.E., D.F.C. (*Vice President*)

   A. A. Dyson, O.B.E. (*Member*)

   G. A. Taylor (*Member*) (*Honorary Treasurer*)

   G. D. Clifford (*Honorary Secretary*)

5. To appoint Honorary Solicitors.

   The Trustees recommend the re-appointment of:

   Mr. C. Gray Hill, 6 Gray's Inn Square, London, W.C.1.

6. To appoint the Honorary Accountant.

   The Trustees recommend the re-appointment of:

   Mr. R. H. Jenkins, F.C.A., 42 Bedford Avenue, London, W.C.1.

7. Any other business.

By Order of the Trustees,

(*Signed*) G. D. CLIFFORD

Honorary Secretary

Brit.I.R.E. Benevolent Fund

The Twentieth Annual Report

The Trustees of the Benevolent Fund have pleasure in reporting to subscribers on the work of the Fund for the twelve months ended 31st March 1961. The Accounts and Balance Sheet are published on page 456 of this Journal.

Why a Fund?—Every professional body has found it necessary to establish means whereby it can give help to those of its members who experience temporary difficulties through unemployment or ill health, and particularly to the dependents of a deceased or disabled member.

When the Brit.I.R.E. was incorporated under the Companies Act in 1932 a few members believed that their own Institution should have similar facilities for helping colleagues in time of need. Such efforts are all too often hindered by a slow start, but gradually the donations built up and the formal establishment of a Brit.I.R.E. Benevolent Fund, administered through Trustees, became possible when the subscribers held their first annual meeting on 28th June, 1941 for the purpose of approving accounts and electing the first Trustees.

Since then, over £4000 of the Fund's income has been distributed to members or the dependents of deceased members to help them during difficulties, in addition to over £2000 donated to schools who have provided the boarding and education facilities for the children of deceased members.

In the early days of the Fund it was, regrettably, impossible to give all the assistance that the Trustees would have liked. The figures given, however, will demonstrate to all members of the Institution the necessity for such a Fund and why its work justified the chapter "In Time of Need" in the official history of the Institution.

A challenge to every member.—In the present era of full employment and social security, it may be understandable that the younger members particularly do not fully realize the need for providing some means whereby professional colleagues experiencing difficulties may be helped. It is certainly a matter of great disappointment to the Trustees that with the increasing membership of the Institution there is not a corresponding increase in the number of members who support the Benevolent Fund.

In the last ten years grants made by the Trustees have remained at a reasonably constant figure and because of this reserves of over £10,000 have been built up providing an interest income of nearly one-third of the total annual revenue of the Fund. This has, however, only been possible because there has not been a significant increase in the calls made upon the Fund. The Institution is, however, one of the youngest of the professional bodies and in years to come must expect a very great increase in the number of members and dependents who may look to the Benevolent Fund for help. If the Trustees are not to fail in giving adequate help, a much greater investment income is required *coupled with better support from the entire membership.*

Mutual co-operation.—Non-subscribers to the Fund should also note that the income of the Benevolent Fund is not devoted solely to giving financial grants to individuals. The Trustees have always been concerned with the need to provide for the welfare and education of children of deceased or disabled members. In this connection the Institution enjoys the co-operation of three schools which are independent of State aid, and which rely mainly on the support given by professional and other bodies. These schools, which provide education and boarding facilities for children deprived of one or both parents are:—

Reed's School (for boys of 11 years upwards who have reached grammar school entrance level or passed the public schools' common entrance examination).* The School, which is at Cobham, Surrey. accommodates 290 boarders and provides education up to G.C.E. "A" level. Every year the Trustees of the Institution's Benevolent Fund set aside a proportion of the income of the Fund for the purchase of a Bursary at Reed's School. Each Bursary, which costs £500, is used for a child nominated by the Trustees and goes towards the cost of the boy's education, boarding and clothing from the time of admission until leaving.

Four Bursaries have so far been purchased and with the continued support of members the Trustees hope to maintain their support of the School in this way. One boy nominated by the Trustees has passed through the School and is just completing his further studies for a professional career as an architect.

Royal Wolverhampton School (for boys and girls from 5 years upwards). Three separate schools are maintained—Junior and Senior Boys' and Girls'. The curriculum of the latter two Schools is designed to prepare pupils from the age of 11 years for the G.C.E. at both "O" and "A" level, or to devote their studies to the secondary modern school standard according to their ability. With the closing of Reed's Girls' School, two children nominated by the Trustees were transferred to the Royal Wolverhampton School.

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* Until 1955 there was a boarding school for girls. Rising costs and inadequate income forced the Governors to the decision to close the girls' school. A sad commentary on the need for supporting Benevolent Funds!

Both were successful in the G.C.E. "O" level examinations. The elder is now employed on secretarial work, and the younger girl, who only left the school in July, is undertaking a specialized course in commercial art.

Royal Wanstead School. This School is one of the very few of its kind which provides boarding school facilities for children from 5 to 11 years and then divides for further education according to secondary modern or grammar school level.

The School has its buildings for the junior children and the senior boys at Wanstead and the senior girls' school is situated at Sawbridgeworth, Hertfordshire.

All the above schools continue to be supported by the Trustees and it is hoped that every member will appreciate the importance of this aspect of their work.

Individual help.—Grants made by the Trustees during the year have mainly concerned the cases referred to in the previous annual report. Some new applications before the Trustees had not definitely required financial help during the period of this report but the Trustees gave advice and help regarding pensions or other income to which they were entitled. In some of these cases the Trustees do make a grant to enable the applicant to meet accrued liabilities pending the receipt of a regular income. An example is that of a member who developed multiple sclerosis (referred to in the last annual report). This member has now been able to secure for himself and his family a pension and income from other sources adequate to meet their requirements.

The Associate Member who had suffered serious illness and disability for many years had to undergo yet a further operation from which he never recovered. His widow has, however, undertaken employment and the eldest son, who was accepted into the Royal Wolverhampton School, has now embarked on a career. The Trustees believe that this family will now be self-supporting, although there is a younger child whom the Trustees may nominate for entry into a boarding school when old enough.

The case of the widow of an Associate Member with three young children which has been the concern of the Trustees since the immediate post-war years, is now being brought to a close. The youngest child has just finished her education at the Royal Wolverhampton School and this family will no longer require financial assistance.

A cash grant was also made to an Associate Member who, because of prolonged ill health and consequent unemployment, had exhausted his private savings.

Donations were also made to the London Associa-

tion for the Blind and to the Royal Hospital for Incurables.

The Accounts.—Income and expenditure have already been commented upon but the Trustees again wish to record their thanks to Electric and Musical Industries Ltd., and to the Radio Industries Club of London and the Radio Industries Club of Manchester for their generous annual donations.

The number of members who made individual contributions to the Fund was only 1159 compared with 1304 in the year ended 31st March 1960. This difference accounts for the fact that total subscriptions during the year fell by £260. It is hoped that the remarks contained in this report will encourage more members to support the Fund, particularly by a deed of convenant. As a result of last year's appeal on this subject forty-three members now subscribe by a deed of covenant.

Acknowledgments.—The Trustees continue to be grateful for the help and advice on legal and accountancy matters given by the Honorary Solicitor, Mr. C. Gray Hill, and the Honorary Auditor, Mr. R. H. Jenkins. Thanks are also expressed to members who assist the Trustees in their work by visiting families to investigate individual circumstances and by drawing the Trustees' attention to members or their dependents in need.

Schedule of Investments as at 31st March, 1961

		£	s.	d.
£200	3% Savings Bonds 1960/70	191	3	6
£200	3% „ „ 1965/75	182	15	9
£1,500	3½% War Loan	1,157	15	9
£200	3% British Electricity Guaranteed Stock 1968/73	155	19	6
£2,000	4% British Transport Guaranteed Stock 1972/77	1,863	14	10
£4,000	4% Consolidated Stock	3,526	16	0
£200	5½% Exchequer Stock 1966	201	2	0
£800	5½% Commonwealth of Australia 1977/80	788	2	7
300	7% Great Universal Stores Ltd. Pref. Stock	354	2	0
200	4½% Great Universal Stores Ltd. Pref. Stock			
£50	Associated Newspapers Ltd. 200 5/- Deferred Shares	166	4	6
£100	6% L.C.C. Loan 1975/78	99	4	4
£200	6½% Liverpool Corporation Mortgage	200	0	0
£300	5½% Middlesbrough Corporation Mortgage	300	0	0
£100	6% Associated Electrical Industries Debenture 1978/83	98	10	0
300	Units Commonwealth Trust	150	0	0
500	Shares Falcon Trust Ltd.	125	0	0
£60	G. Nott Industries Ltd. 300 Ordinary Stock of 5/-	368	18	7
£100	Bowater Paper Corporation Ord. Stock	290	17	4
		£10,220	6	8

(Market Value as at 31st March, 1961
£8,755 . 0 . 0.)

THE BRITISH INSTITUTION OF RADIO ENGINEERS

BENEVOLENT FUND

INCOME AND EXPENDITURE ACCOUNT FOR THE YEAR ENDED 31st MARCH, 1961

1960 £		£ s. d.	£ s. d.	1960 £		£ s. d.	£ s. d.
400	Grants and Donations		430 10 0	1,355	Subscriptions and Donations		1,095 6 10
100	Purchase of Bursaries		330 0 0	385	Interest on Investments (Gross)		447 8 10
13	Postage and Stationery		13 2 9				
20	Sundry Expenses		— — —				
	Balance being surplus for the						
1,207	year carried to Reserve Account		769 2 11				
£1,740			£1,542 15 8	£1,740			£1,542 15 8

BALANCE SHEET AS AT 31st MARCH, 1961

1960 £		£ s. d.	£ s. d.	1960 £		£ s. d.	£ s. d.
	RESERVE ACCOUNT				FIXED ASSETS		
	Balance as at 1st April 1960	9,809 0 9		9,560	Investments at Cost		10,220 6 8
	Add Surplus for the year	769 2 11			(See Schedule attached)		
9,809			10,578 3 8		CURRENT ASSETS		
				118	Income Tax Repayment Claim	264 8 3	
				39	Cash at Bank	36 10 2	
					Amount due from The British Institution		
				92	of Radio Engineers	56 18 7	
							357 17 0
£9,809			£10,578 3 8	£9,809			£10,578 3 8

For Trustees:—
Signed: G. A. MARRIOTT (Chairman)
J. L. THOMPSON
G. D. CLIFFORD (Honorary Secretary)
G. A. TAYLOR (Honorary Treasurer)

I have audited the above written Balance Sheet dated 31st March, 1961, in respect of the Benevolent Fund. I have received all the information and explanations I have required and in my opinion the Balance Sheet represents the true and accurate state of the Benevolent Fund.

42, Bedford Avenue,
LONDON, W.C.1.
25th July, 1961.

R. H. JENKINS, Chartered Accountant,
Honorary Auditor

The Reliability of Components in Satellites

By

G. W. A. DUMMER,
M.B.E., (*Member*)†

Summary: The environmental conditions to which space vehicles are subjected place severe stresses on the components and the severity of these special conditions is discussed—i.e. shock, vibration, acceleration, temperature extremes, low pressure, solar radiation, cosmic rays and x-rays, ozone content of space, dissociated gases, etc. The probable effect of these environments on average components is discussed and hermetic sealing and protection problems are examined. The present programme of "special quality" components for guided missile use is described and some of its difficulties outlined. The development of high quality components for use in undersea cables for 20 years' life is also relevant and is described. A summary is given of the most reliable types of components for use in satellites. Finally, the possible effect of micro-miniaturization techniques is discussed and in particular the effect of space environments on solid circuits.

1. Environments

Components in space vehicles will be subjected to many new environmental conditions and protection from these environments, together with the simultaneous requirements for very high reliability, will present many problems. From knowledge obtained to date, the environmental conditions may be summarized as follows:

(1) Launching shocks, acceleration and vibration.
(2) Temperature extremes.
(3) High rates of change of temperature.
(4) Low pressure (vacuum).
(5) High ozone content (100 times that at sea level).
(6) Solar radiation effects.
(7) Weightlessness or zero gravity.
(8) Cosmic and x-ray radiation.
(9) Micro-meteorite dust erosion.
(10) Dissociated gases (oxidization effects).

Some of these, such as launching shocks, acceleration and vibration, are already experienced in guided missiles and data obtained can be valuable in estimating possible more severe effects which will be caused by higher power rockets for satellite launches.

1.1. *Launching Shocks, Acceleration and Vibration*

The present maximum shock figures in the United Kingdom for guided missiles are 50 *g* for 12 ms and 100 *g* for 6 ms and vibration of 10 and 20 *g* at frequencies from 30–5000 c/s. These values are used as test figures for electronic equipment and components in missiles, and some experience has already been obtained on components, whilst typical accelerations in space vehicles are given in Table 1.

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† Royal Radar Establishment, Great Malvern, Worcestershire.

Table 1

Acceleration in Typical Space Vehicles
(After Morrison[1])

	First stage	Second stage	Third stage	Payload
Able-1 (*Pioneer II*)	11 *g*	7 *g*	30 *g*	30 *g*
Able-3 (*Explorer VI*)	11 *g*	7 *g*	13 *g*	4 *g*
Thor-Able-4 (Space probe)	11 *g*	8 *g*	20 *g*	—
Atlas-Able-4 (Lunar probe)	6 *g*	5 *g*	7 *g*	—

The effect of acceleration is mainly to deflect balanced mechanisms, such as relays, and to provide sustained loads which may overstress materials, structures and components. Provided care is taken in design, the effects are not normally serious.

The main effect of vibration on components is to set up natural resonances either within the component itself or in the mounting. In tag-strip-mounted components, the length of the mounting lead, its diameter and the weight of the component, all affect the natural resonance of the component under vibration. The tightness with which the component is soldered to the tags also affects the resonant frequency. It has been found that resonant frequencies for small components with weights from 0·01 oz–0·4 oz and lead lengths of 1·2 in, wire diameters 0·025 in–0·042 in, are in the 200–450 c/s range. With lead lengths reduced to 0·5 in, resonances are in the 1000–1500 c/s range.

Methods of avoiding difficulties due to vibration are to shorten the lead lengths so as to raise the resonant frequency and minimize the amplitude, to use thicker lead wires, and, with components weighing over $\frac{1}{4}$ oz, to clamp them to the chassis. Even with short leads, the effect of lead stress should not be neglected, and there is a decrease in resonant frequency with time for small components subjected to continuous vibration due to fatigue effects. Potentiometers and variable capacitors can be seriously affected by vibration and should be pre-tested before use. Heavy components such as transformers must be mounted extremely securely to withstand the shocks of launching, and potting techniques are an effective method of preventing damage to components by shock and vibration. It is usual practice, where printed wiring boards are used, to cement all small components to the board.

1.2. Temperature Extremes

These are extremely difficult to estimate and some recent unclassified American specifications figures give $-65°$ F to $+1200°$ F for military satellites. There are three main conditions affecting satellite temperature:

(i) The designed operating temperature, i.e. normal running and pre-flight testing.
(ii) Aerodynamic heating during the launch period.
(iii) The final attained temperature in orbit, including the sun's radiation.

For the first condition, most electronic equipment is now transistorized (with the exception of the transmitter valve or valves) and therefore low voltages can be used with consequent low dissipation in the components (again, with the exception of the transmitter valve or output stages). By using pulse techniques with "bottomed" transistors, signal voltage dissipation can also be kept low, and a recent digital computer design using 300 transistors has a total power consumption of less than one watt. Most of the internal heat is dissipated by the transmitter valve, and may be several watts. As it is not normally possible to cool by blowers or liquids (which consume power), it is necessary to design so that the total temperature rise is as low as possible in the space provided by using the minimum of power.

The second condition depends on many factors—the power of the launching vehicle and therefore the speed, the method of heat isolation from the nose cone, which may itself rise to several hundred degrees Celsius on its outer surface, roughness of the skin surface, etc. Fortunately the time interval is not long and there are several methods of heat isolation available, such as multi-layer skins, expanded plastics and solid inorganic materials, so that with good design

the internal temperature of the equipment should not rise so high as to damage the components.

The third condition is the most important for very long life satellites, and is governed mainly by condition (i), the designed temperature. The sun's radiation heating at certain parts of the earth's surface is over 1000 watts per square metre, but a great deal of the solar spectrum is, of course, absorbed by the earth's atmosphere. At 600 000 ft the sun's radiation spectrum should be complete and practically undisturbed by absorption at about 1500 W/m².

In a stabilized satellite the sun's rays will heat one side only, the other side being at a temperature depending, amongst other factors, on the distance from the earth, whilst in spinning or orbiting satellites the conditions will be quite different. The temperature distribution of the atmosphere above the earth is shown in Fig. 1, from which the low temperature extreme can also be seen. Nitrogen-filled spinning satellites with white-painted or highly-reflecting surfaces should result in little temperature rise over normal.
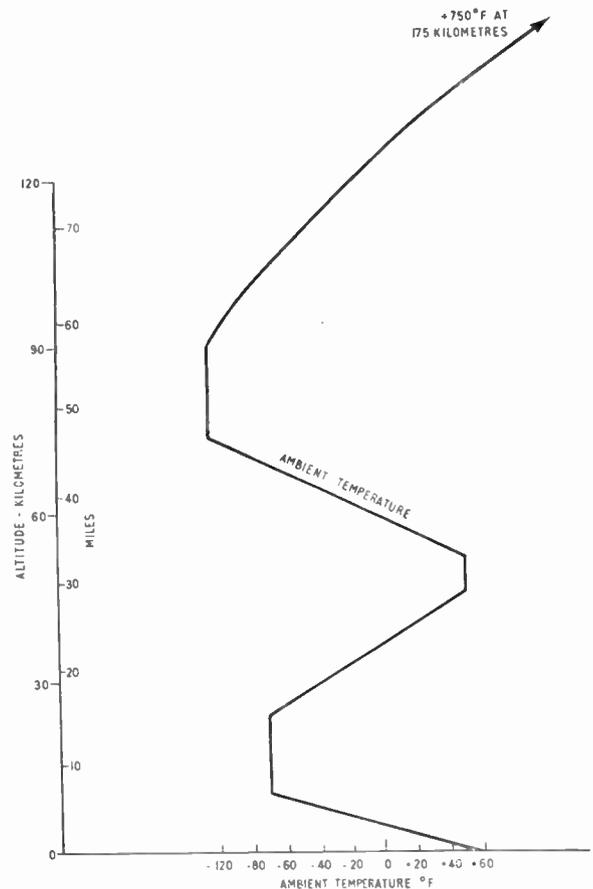
Fig. 1. Variation of the temperature of the atmosphere with altitude. (After Wacholder and Fayer.[4])

The effects of high and low temperatures on components have been fully described elsewhere.[2] Until more accurate data are available, it is difficult to predict temperature rises and the safest course is to design condition (i) as efficiently as possible.

1.3. *High Rates of Change of Temperature*

As discussed in Section 1.2, the rate of change of temperature of the nose cone may be over 100° C within a few minutes, but provided adequate heat isolation of the components is provided, this should not cause any undue difficulty.

1.4. *Low Pressure (Vacuum)*

As the satellites recede from earth the pressure reduces with increasing altitude and approaches a perfect vacuum as a limit. Typical values for pressure against altitude are given in Table 2.

Table 2

Variation of Pressure with Altitude[3]

Altitude km	Pressure lb/in²
15	1·7
30	0·16
60	$0·465 \times 10^{-2}$
90	$0·256 \times 10^{-4}$
300	$0·258 \times 10^{-9}$

Unless the equipment is sealed, the effects of these absolute pressures may cause difficulties due to corona discharge, arc-over, absence of damping in vibration, explosive decompression and vaporization of materials, especially combined with influence of high temperatures. Considerable study will be needed to determine the effects of long-term vaporization of metals, explosives, organic materials and liquids.

From the component design point of view, the effects of altitudes up to 100 000 ft have been fully described elsewhere,[2] but, in summary, corona discharge and flash-over must be watched where transmitter valves are concerned, as also must the absence of air damping in vibration and the boiling of fluids at lower temperatures.

It is axiomatic that any space equipment must be sealed and the problem then becomes one of normal pressurization design as for existing airborne equipment. Maximum pressure differences will not exceed 14·7 lb/in² and techniques for coping with this pressure are well known. Long-term drying-out of trapped moisture must, however, be guarded against and this problem is dealt with later in the paper.

1.5. *High Ozone Content*

The ozone concentration in the stratosphere and the chemosphere has been found to be relatively high in the upper atmosphere and ranges from one part per million at lower altitudes to eleven parts per million at approximately 100 000 ft. The main ozone layer (ozonosphere) ranges from 30 000 ft to 150 000 ft. The damaging effects of ozone on materials is due to chemical reaction such as occurs with rubber, but very little is known and some work may have to be done to determine the possible seriousness of high ozone content.

1.6. *Solar Radiation*

Innes[7] points out that the sun as a black body radiator pours out energy giving a flux of 2 cal/cm²/ min at a distance of one Astronomical Unit, and estimates a typical earth satellite will receive about $1·4 \times 10^{14}$ photons/cm²/s with $E > 4$ eV. Most of the solar energy is in the region of the visible spectrum and is therefore useful for energizing solar cells, whilst the infra-red radiation produces a heating effect. The distribution of solar energy is shown in Table 3.

Table 3

Distribution of Solar Energy in Space
(After Di Taranto and Lamb[3])

Type	Wavelength Å	Per Cent
Far ultra-violet	1 000–2 000	0·2
Near ultra-violet	2 000–3 800	7·5
Visible	3 800–7 000	41
Infra-red	7 000–10 000	22
Infra-red	10 000–20 000	23
Infra-red	20 000–100 000	6

The ambient temperature given by Wacholder and Fayer (see Fig. 1) in their chart for low orbit vehicle environments[4] is approximately 750° F at 110 miles, but the actual internal satellite temperature depends on its surface absorption of the sun's radiated energy and the internally generated heat.

1.7. *Weightlessness*

This is a condition which is extremely difficult to simulate in the laboratory, and little is known about possible long-term effects. Obviously, instruments which depend upon gravity for their operation cannot be used. Also there is no convection cooling in this condition.

1.8. *Cosmic and X-ray Radiation*

There is still considerable controversy over cosmic radiation, and the effects of radiation surges due to

solar flares are the subject of speculation. Radiation effects on materials and components are not easily definable, but the satisfactory performance of equipments and components used so far in satellites indicates this may not be a particular difficulty. Next to human beings, semi-conductor materials used in transistors and diodes are most susceptible to damage from the protons, electrons and secondary radiation, e.g. neutrons and gamma rays, and this is discussed in more detail later in Section 4. Instruments carried aboard satellites and lunar probes have revealed the existence of two zones of high intensity corpuscular radiation surrounding the earth (the Van Allen belts). *Pioneer III* established data as far out as 64 000 miles, and *Pioneer IV* established data to 400 000 miles. More recently *Explorer VI* has revealed new radiation patterns near the earth.[5] The general pattern of the radiation is that of a torus (inner Van Allen belt) lying in the equatorial plane round the earth, with the outer Van Allen belt further out and of a more indefinite character. The long-term effects of x-radiation and cosmic rays have yet to be determined, but effects will be mainly on semi-conductors and this is discussed later.

1.9. *Micro-meteorite Dust Erosion*

Direct measurements of skin erosion and sputtering effects on the satellite *Vanguard III* have shown that over 2000 impacts were recorded, but the completion of the analysis of data is awaited. The main effect of micro-meteorites is to cause erosion of surfaces, in particular on the solar reflectors used for space power systems. It has been shown that particles as light as 10^{-16} grammes will cause craters which will materially reduce the specular reflectivity of optical surfaces. As this is mainly a surface effect, the operation of components inside the vehicle should not normally be affected.

1.10. *Dissociated Gases*

Atomic oxygen will react with metals such as iron, copper and silver and with many organic materials. The effects can be generalized as an oxidization at a high rate. Metals such as aluminium which form an adherent oxide film may only form a thicker oxide film. The effects of other dissociated gases are not yet known and will need considerable study.

2. Hermetic Sealing and Protection Problems

Experience has shown that the best protection from humidity, dust penetration and other earth environments is to seal the equipment completely, filling with dry air or an inert gas. In order to prevent flash-over of transmitter voltages and to operate equipments at equivalent sea level pressures, it is also essential to seal the equipment hermetically. Techniques of sealing by conventional standards, e.g. solder seals, etc., are well known, but long-term leakage rates may need more research.

Potting techniques are also satisfactory as a protective medium, having the additional advantage of protecting components against shock and vibration. There are so many factors which are unknown in the satellite environments that it would appear that potted units in a sealed container might offer the best protection.

Most of the effects of potting resins on components are known[2] and examples of potted constructions are now some ten years old, with no visible or measurable deterioration in the components. It is essential that the correct techniques be adopted and many known pitfalls avoided. The advantage of potting techniques over hermetic sealing is mainly one of mechanical protection during launching shocks, and of additional protection against possible radiation effects. As transistors and miniature components are used, this further aids the technique of potting assemblies, although there may be a weight increase over complete hermetic sealing techniques using printed wiring boards with components cemented to the board.

3. High-quality Components

The development of high quality conventional components has followed two separate lines: (1) special components for use in undersea repeater cable amplifiers, and (2) special components for use in guided missile electronics systems. Many lessons have been learnt in the development of these components, which can be put to use in space vehicle equipment.

It is useful to consider the possible failures of components which are manufactured under "clean" conditions and operated under conditions of temperature equilibrium with no shock or vibration after the initial laying of the cable.

Before considering the details of failures, the occurrence of failures in repeaters already laid down on the sea-bed has been summarized by New.[6] He shows that progressive refinements have achieved a level of reliability in the 1950's which is some 10–100 times better than that of the first submerged repeaters in the 1940's. The cost of developing special components of this quality is obviously high, but in the case of satellites where no repair is possible, this can to a certain extent be discounted.

Failures of components may occur due to many causes—bad design, mis-use, mechanical, chemical or physical methods of failure. Provided the first two factors have been avoided, mechanical failures may arise during launching shocks, which may be eliminated by pre-flight vibration and shock testing. Contact problems may occur due to oxidization of

contacts with high ozone content, but this is a field for further research. Chemical action is probably the most likely cause of failure in components operated for extremely long periods of time under satellite environmental conditions. Whilst most chemical reactions need moisture for electrolytic action, it is not known what changes will take place under environments of radiation activity and extreme vacuum. For instance, the electrolyte of electrolytic capacitors may dry out, causing failure. Contraction of paper capacitor windings due to drying out of moisture present under vacuum environment may cause dislocation of the tabs making pressure contact to the foils. The drying out of the moisture ions which are inevitably present in many materials of which components are made, may be a considerable source of difficulty and, again, potting techniques may delay this effect for a considerable time—months, or even years. The effects of diffusion or migration will have to be studied, such as that which occurs from the p.v.c. sheath to the dielectric of polythene insulated radio frequency cables. Stress relaxation may occur in plastic materials which are clamped in a way which depends on the back stress built up in the plastic to hold it firm, for example, p.t.f.e. buffer blocks in relays, and plastic film dielectric capacitors. The failure of metal springs in switches and similar components due to fatigue is a problem which might be accelerated by radiation effects, and again much more study is needed. Surface films can be formed on some plastics quite readily under the influence of ultra-violet light, so that care is necessary in design. De-polymerization may also occur in some circumstances in plastics in space vehicles.

In the case of the development of special components for guided missiles, considerable stress has been laid on the mechanical design of the components. An essential requirement was severe vibration testing of components both to destruction and to given limits over the frequency range 30–5000 c/s. The special quality components for missiles were selected from the Type Approved Service components as being the best available under military specifications. Components from each manufacturer of a particular type were evaluated under pan-climatic tests in addition to vibration and shock tests, and after selection of a particular manufacturer, further tests to destruction were done to provide adequate safety factors. One of the problems in ensuring high reliability of a component is that of continuous production, whilst the component must also continuously meet a very tight specification. This specification lays down acceptance quality levels throughout all stages of manufacture, and also many tests of the final product to eliminate potential failures. This programme naturally takes considerable time and although the specifications have now been

written for a number of the commonly used components, i.e. resistors and capacitors, the final stages have not yet been put into effect. However, it is obvious that this is the type of component which should be used in space vehicles because of the experience already gained in developing this missile type of component, and seems the only method which can be seen at the moment to ensure the high quality required in satellite conditions. A list of components in this category is given in Table 4.

Table 4

Components being specially produced for Guided Missiles

Component Designation†	Component Type	Value	Rating and Temperature
RWV3–J	Fixed resistor, vitreous enamel, wirewound.	$10\,\Omega$ to $4 \cdot 7\,\mathrm{k}\Omega$	1·5 W at 70° C
RC2–D, E, F.	Fixed resistor, non-insulated, cracked-carbon film, Grade 1. (High stability.)	$10\,\Omega$ to $5\,\mathrm{M}\Omega$	(D) ½ W at 70° C (E) ¼ W at 70° C (F) ⅛ W at 70° C
RC7–H, K.	Fixed resistor, insulated, carbon composition film, Grade 2.	$10\,\Omega$ to $10\,\mathrm{M}\Omega$	(H) ½ W at 70° C (K) ¼ W at 70° C
RVC–12A	Variable resistor, moulded resin/ carbon track.	$100\,\Omega$ to $5\,\mathrm{M}\Omega$	¼ W at 85° C
CET–12	Electrolytic capacitor with tantalum anode.	50, 140, 250 μF	150° C
CET–11	Electrolytic capacitor with tantalum foil electrodes.	0·3 to 200 μF	125° C
11 P.C.R.	Sealed two-compartment relay.	1 change-over	125° C

† Selection of the manufacturers' products which have proved specially suitable for this development has been done in close collaboration with the guided weapon industry, and it would be inappropriate to mention specific manufacturers' names here.

4. Microminiaturization

It is obvious that the size of components must be reduced for space vehicles. This, however, raises many difficulties in manufacture where scaled-down components are developed by conventional techniques. A point is reached when reliability is endangered by sheer construction and handling problems.

Microminiaturization techniques offer new possibilities in enhanced reliability with small size, but have yet to be proved. The systems most likely to produce very high orders of reliability are those of micro-

circuits, which it is hoped will give a ten-times gain over the best conventional components, and solid circuits, for which it is hoped a hundred-times gain will be reached. These are, of course, target figures, but there is reason to believe that they are theoretically possible because of the extreme care in manufacture and in the accurate process control essential in their fabrication. High purity materials are also used and in the case of the solid circuit a single homogeneous material only is used.

It is not intended to describe the processes in detail as this is to be done in a later paper,[8] but results which have been obtained to date on micro-circuit techniques have shown remarkably few failures, even in the development and pilot production stages.

There are still problems to be solved in both techniques—those of interconnection and cooling—but considerable work is being done on both these problems and there is every hope that solutions will be reached.

The specific problems of space environments on solid circuits have been theoretically examined and are summarized below:

As is well-known, radiation and high energy particles can change the electrical properties of a semi-conductor. Some changes are transitory and cause spurious signals, others can cause a permanent alteration to constituents of the crystal structure and therefore permanently affect the electrical properties. A solid circuit will be just as sensitive to radiations and high energy particles as a conventional transistor, and may be more so because all the "components" in a solid circuit are made of semi-conductor material. The degree of sensitiveness of a solid circuit to space environments is directly related to the way it is protected or packaged. The term "packaging" must be taken in its widest sense and must include not only the case around the solid circuit but also the walls of the space vehicle.

The effects of space environments described previously can now be examined theoretically on solid circuits.

4.1. *Shock, Vibration and Acceleration*

Because of its small mass and absence of long leads, it is reasonable to suppose that a satisfactory performance will be obtained under quite heavy shock, vibration and acceleration. If a solid circuit is compared with a conventional transistor circuit, then in addition to the advantage of compactness there is approximately an 80% reduction in interconnecting leads, and therefore this should be the best construction to withstand mechanical stresses imposed during launching.

4.2. *Temperature Extremes*

Transistor circuits are temperature-sensitive and circuits are usually designed so that these changes are compensated. A solid circuit will be just as temperature-sensitive as a conventional transistor circuit, with the additional factor that the components such as resistors, capacitors, will also be temperature-sensitive, and a great deal of work remains to be done on this problem. In principle, it may be possible to design solid circuits which are relatively insensitive to temperature over a restricted range, but few data are available at the moment.

4.3. *Low Pressures*

Low pressures in themselves should not affect a semi-conductor device. This also applies to solid circuits. To prevent any change in characteristics due to the extraction of the ambient gas in a solid circuit can, the can sealing must be as perfect as possible.

4.4. *Solar Radiation*

Heat radiation from the sun will, of course, heat the solid circuit if temperature control or shielding is not used in the space vehicle. This has previously been discussed under "Temperature Extremes". The visible light from the sun will not affect the solid circuit provided the encapsulation is opaque, and as far as can be seen, other radiations from the sun are unlikely to affect a solid circuit operating inside a space vehicle.

4.5. *X-Rays and Cosmic Rays*

Typical impurity concentrations in a semi-conductor are about $10^{15}/cm^3$, so that even if the secondary particles generated by primary cosmic rays made permanent changes in the semi-conductor, the effects on a device's electrical properties are expected to be small, but this seems to be the main area of danger, and much work remains to be done.

4.6. *Aurorae, etc.*

As the energies are expected to be low, they should have no effect on an encapsulated solid circuit; similarly for the ozone content and dissociated gases. Certainly, as transistorized equipment appears to have operated successfully in space vehicles under protected conditions, there is no reason to suppose that solid circuits, if properly designed, will be adversely affected. It is interesting that some semi-conductor devices have now been in continuous operation for over 30 000 hours, with no appreciable change in characteristics.

It is expected, therefore, but cannot yet be proved, that both micro-circuits and solid circuits will be more reliable than conventional transistors and components, and for some future space vehicles there is no doubt

that these types of construction will be used. However, it may be some time before the theoretical reliability can be proved, and possible radiation effects will have to be evaluated before their widespread adoption in satellites.

5. Acknowledgments

The author would like to acknowledge the assistance from his colleagues at R.R.E., in particular Dr. J. W. Granville, Mr. N. Griffin and Dr. J. S. Greenhow, and also the help received from Mr. A. A. New and Dr. R. Innes.

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Communications Satellite Developments

Project TSX: U.S.–G.P.O. Space Co-operation

Following an agreement between the U.S. National Aeronautics and Space Administration and the American Telephone and Telegraph Company, the British Post Office is to participate in tests of a new communications satellite known as Project TSX. The satellite, which is of the active type and is being designed by the Bell Telephone Laboratory, is to be launched by N.A.S.A. early in 1962. The tests are to include the transmission of television signals and multi-channel telephony between the A.T.T. Co. ground station at Rumford, Maine, U.S.A., and the ground station which the Post Office is erecting on the Lizard, Cornwall.

The tests are additional to those announced earlier this year (see the *Journal* for May 1961—page 408) and which involve Project *Relay*, an active satellite, and Project *Rebound*, a passive satellite of the balloon reflector type. Project TSX is expected to provide additional design information concerning satellite communication systems; in particular, it is to use higher frequency bands than those planned for Project *Relay*.

Satellite Communications Transmitter

A contract for the supply of a transmitter for use by the G.P.O. in satellite communication experiments to be carried out next year in co-operation with the American authorities has been awarded to Standard Telephones and Cables.

The equipment will be installed in a room built into the 85-ft diameter steerable aerial now being erected on a site at Goonhilly Down, Cornwall. The transmitter will operate in the 2000 Mc/s band, and will deliver a frequency-modulated output of 10 kW. Additional items to be supplied by S.T. & C. include power equipment for the transmitter and a water-to-air heat exchanger unit.

The present programme calls for the whole transmitter to be installed on site and fully operational by April 1962. An active repeater communication satellite to be launched by the U.S.A. authorities will enable tests to be conducted on television transmission and two-way speech communication between Cornwall and the American ground station at Rumford, Maine.

Computer for G.P.O. Satellite Communications System Radio Station

The British Post Office has ordered a National-Elliott 803 Electronic Digital Computer for use at its satellite system radio station on the Lizard, Cornwall, in connection with Transatlantic tests of communication satellites next year.

The computer will be used to convert predicted orbital information derived from the U.S. Minitrack world-wide network of tracking stations into steering instructions on punched tape for controlling the 85 ft diameter paraboloid steerable aerial at the station. At the appropriate time, the steering instructions on the punched tape will be fed into the electronic controlling equipment of the aerial which will then be pointed in the direction of the satellite as it appears above the horizon. Throughout the course of the satellite, as it rises to its zenith and falls towards the horizon, the aerial will continue to be pointed automatically at the satellite, with a precision of the order of one-tenth of a degree.

INSTITUTION NOTICES

National Certificates and Diplomas

The General Council of the Institution has been invited to nominate a member to serve on the Joint Committee for National Certificates and Diplomas in Electrical Engineering.

In recent years an increasing number of colleges in Great Britain have been developing Higher National Certificates syllabuses with increasing radio and electronics content in the A1 and A2 years and with specialist endorsement subjects designed to meet the additional requirements for admission to membership of the Institution.

This fact has now been recognized by the Joint Committee set up under the aegis of the Ministry of Education and has led to the present invitation to the Institution to appoint a member to serve on the Joint Committee.

Advisory Council for Technological Education

In England and Wales there are ten Regional Councils for further and/or technological education. The Regional Advisory Council for Technological Education for London and the Home Counties was formed as a result of conferences convened by the London County Council on the initiative of the Ministry of Education in 1946.

Primarily the Council exists to ascertain the needs of industry and commerce for technical and commercial education in the region and to advise education authorities in membership so that they can make the necessary provision for courses in their institutions of further education. It seeks to co-ordinate the work of the region to avoid unnecessary duplication.

Much of the most valuable work of the Council is done by industrial advisory committees, on which representatives of regional bodies of employers and employees in a very wide variety of industries meet educational representatives to plan developments from the standpoint of the region as a whole.

The Council of the Institution has now been invited to nominate a member of the Institution to serve on the London and Home Counties Advisory Committee for Electrical Engineering (including Radio and Telecommunications).

Completion of Volume 22

This issue completes Volume 22 of the *Journal* which covers the period July–December 1961. An index to the volume will be circulated early in 1962.

Members may have their own issues of Volumes 21 and 22 bound for 16s. 6d. per volume (postage extra: 3s. Great Britain; 4s. Overseas). The issues and appropriate indexes should be sent to the Publications Department, at 9 Bedford Square, London, W.C.1, with remittance.

Symposium on Data Transmission

A one-day symposium of papers on Data Transmission will be held on Wednesday, 3rd January 1962. at the London School of Hygiene and Tropical Medicine, Keppel Street, Gower Street, London. W.C.1. It will consist of two sessions starting at 10 a.m. and 2 p.m. The papers will include:

"Telephone Circuit Evaluation for Data Transmission" by K. L. Smith, J. Bowen and L. A. Joyce.

"Modulation Systems for Data Transmission" by A. P. Clark.

"Data Collection Systems" by J. A. Pearce.

"Comparison of P.M. and F.M. for Serial Data Transmission over Telephone Lines" by F. G. Jenks and D. C. Hannon.

"Data Collection and Distribution" by D. J. Dace.

"Error Correction in Data Transmission Systems" by E. R. Aylott and E. S. Simmonds.

"Recent Developments in Data Transmission" by K. L. Smith.

Tickets will not be required by members.

The 1962 Physical Society Exhibition

The Annual Exhibition of the Institute of Physics and the Physical Society will be held in the Halls of the Royal Horticultural Society, Vincent Square. London, S.W.1, from 15th–19th January 1962.

The hours of opening will be:

Monday, 15th January	2 p.m.–7 p.m.
Tuesday, 16th January	10 a.m.–9 p.m.
Wednesday, 17th January	10 a.m.–7 p.m.
Thursday, 18th January	10 a.m.–7 p.m.
Friday, 19th January	10 a.m.–1 p.m.

Members may obtain tickets from the Institution and are asked to enclose a stamped addressed envelope. In addition special passes for admission on the "Members morning" (Monday, 10.30–2) have kindly been made available by the Institute and Society and those wishing to attend at this time should indicate accordingly.

Joint Meeting with the Institute of Physics

The Institution's Electro-Acoustics Group has been invited by the Acoustics Group of the Institute of Physics and the Physical Society to take part in a meeting on "The Calibration of Microphones and Hydrophones". The joint meeting will be held on Wednesday, 17th January at the Royal Horticultural Society's New Hall, London, S.W.1, at 2 p.m.

The Chair will be taken by Dr. R. W. B. Stephens. Chairman of the Acoustics Group of the Institute and Society, and three papers will be presented:

"A study of errors in the calibration of probe microphones" by E. Aspinall and A. N. Rapsey.

"Problems in the design of an artificial mouth" by Dr. H. S. Leman.

"The calibration of hydrophones" by Dr. R. B. Newman.

Tickets of admission will *not* be required.

Some Telemetry Systems for Space Research

By

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AND

J. H. WHITE†

Presented at the Convention on "Radio Techniques and Space Research" in Oxford on 5th–8th July 1961.

Summary: The paper describes the telemetry systems used in the *Skylark* rocket and in the satellites which are to be launched by American *Scout* rockets. Both these systems are adapted from existing telemetry systems, the *Skylark* from the British 24-channel system and the *Scout* satellite from the *Explorer VIII* rocket.

The first part of the paper indicates the new developments in the British 24-channel system and describes briefly some data reduction equipment. The second part discusses the ways in which the British and American systems differ.

1. Introduction

British space research makes use of the *Skylark* rocket and the American *Scout* satellite. Both *Scout* and *Skylark* use adapted forms of existing telemetry. Had they been developed specifically for space research in satellites and rockets respectively, it is quite likely that a different form would have resulted.

The telemetry in *Scout* will be an adaptation of that used previously in *Explorer VIII*. That in *Skylark* is the well-known British 24-channel system which, for many years, has been used for testing guided missiles. This latter system has already been described.‡

Recent new developments in the British 24-channel system, which have made extensive use of solid state devices, have given the sending equipment a new look. Part I of this paper concentrates upon this aspect

rather than repeats what has been done before.‡ Incidentally, the transmitter used in *Skylark* was designed in 1956 and is therefore of the old pattern.

Part I also includes a brief description of some data reduction equipment which is being developed for use with records from the *Skylark* firings. In missile research, although a large volume of data is usually telemetered during the course of a single flight, only a small amount requires detailed analysis. In space research, nearly all the data require further analysis. Efficient data reduction is therefore essential.

Part II of this paper discusses some of the ways in which the two systems used in *Scout* and *Skylark* differ. The main theme is that whereas they both use telemetry which is basically the same, a detailed comparison reveals some large and interesting differences.

Part 1: The British 24-channel Telemetry System

2. New Developments in the Telemetry Transmitter

Missile instrumentation is commonly called upon to achieve the required performance in a small volume of curious shape. In addition it is required to be highly reliable, simple to maintain and of reasonably low cost.

It seemed likely that by making use of recent advances these requirements could be approached more nearly than hitherto.

Some desirable features of a telemetry transmitter are now considered.

2.1. *Reliability*

The most satisfactory telemetry equipment has been shown to be that which has become familiar over a

long period both to the manufacturer and the users. Each particular application is short-lived, and in order to make use of this characteristic it is desirable to use as many common parts as possible.

2.2. *Flexibility*

In order to achieve reliability by the means mentioned above, each part which is intended to be common must be suitable for a multitude of applications, and all such parts must be mutually compatible.

2.3. *Small Size*

Small equipment is more nearly universal than large equipment because it is more likely to fit the available space in a number of applications—most of which will be unknown at the time of design.

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† E.M.I. Electronics Ltd., Hayes, Middlesex.

‡ W. M. Rae, "Engineering aspects of missile telemetry equipment", *J.Brit.I.R.E.*, **21**, p. 57, January 1961.

2.4. *Ease and Economy of Manufacture and Servicing*

It will be seen that there is a basic incompatibility between the needs of reliability, which demand that common parts be used for many applications, and of small size in a given shape. To achieve the ultimate in miniaturization equipment must be built specially for each job, in one block or unit, in order that the

A block diagram of 24-channel sender is shown in Fig. 1. Some of the basic waveforms are shown in Fig. 2.

When physical quantities are to be measured it is necessary to convert to an electrical equivalent and the method used varies from simple potential-divider circuits to special transducers, depending on the
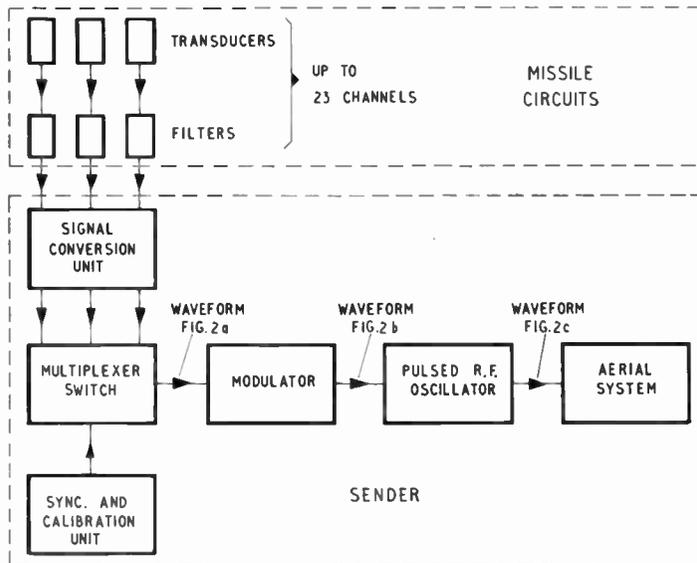
Fig. 1. Block diagram of 24-channel sender.

equipment may exactly fit the shape available and that none of the space be used for interconnecting plugs or other terminals.

The difference in size may be reduced if the sub-units are small and of rationalized dimensions so that a high packing factor may be achieved. The use of semi-conductor devices rather than valves materially assists to keep the sub-units small.

Telemetry transmitters are currently designed to use a number of standard sub-units of modular dimensions. The characteristics chosen for the sub-units render them suitable for use in most presently envisaged missile applications. General use of these sub-units results in substantial economies in development, manufacture, distribution and servicing.

Repair is by replacement of interchangeable sub-units, which requires little skill. Even diagnosis can be avoided in extreme necessity by replacing each unit in sequence until the transmitter functions. Since the sub-units are of wide application spares store-keeping is simplified.

3. The Transmitter

Before discussing the details of the new developments a very brief description will be given of typical transmitting equipment.
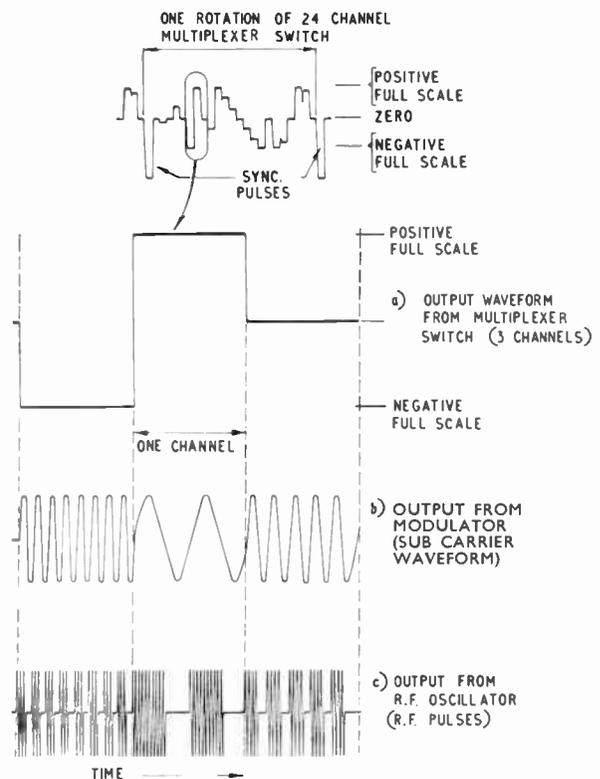
Fig. 2. Some basic waveforms in 24-channel sender.

nature of the measurement. If the transducer output can contain frequencies higher than half the sampling frequency it is necessary to use low-pass filters.

The outputs of the transducers (or filters if used) are then fed to the multiplexer via the signal conversion unit. This latter device matches the input channels to the modulator. The basic multiplexer consists of a 24-way commutator driven by an electric motor. Of the 24 segments, one is reserved for synchronization purposes and at least two others for in-flight calibration.

The output of the modulator is a frequency-modulated signal varying in frequency over the range 130–160 kc/s for full scale input signals. During the synchronization period, the frequency is higher than 160 kc/s (commonly 186 kc/s). This frequency-modulated wave is used to amplitude modulate the r.f. carrier oscillator beyond 100%. Consequently the r.f. oscillator is switched on and off by the sub-carrier waveform.

3.1. *The "Modular Sub-Unit" Transmitter*

Most of the commonly used parts of a transmitter are built as functional sub-units, based on a module of 3 in. × 2¼ in. × ¾ in. Any unit which cannot be accommodated within these dimensions is either divided into two or more units, or built instead within a volume of 3 in. × 2¼ in. × (*n* × ¾ in.). Each unit has a single multi-way plug for all connections accessible on one of the 2¼ in. × ¾ in. surfaces, and all the controls accessible from the other 2¼ in. × ¾ in. surface.

Where possible, piece parts of the various units are also common. For example, an identical container is used for the majority of units, as is the base casting which is common except for keyways drilled in a different way for each unit to avoid errors in assembling the units to the transmitter chassis.

With the exception of the r.f. oscillators, the units are filled with a rigid polyurethane foam of low dielectric constant, which supports the components against shock without materially increasing the weight of the unit. Figure 3 illustrates how the appearance of a transmitter built on these lines differs from earlier designs. Figure 4 is a block diagram of a typical modular transmitter.

NEW TYPE TRANSMITTER NEW TYPE POWER UNIT

OLD TYPE TRANSMITTER OLD TYPE POWER UNIT
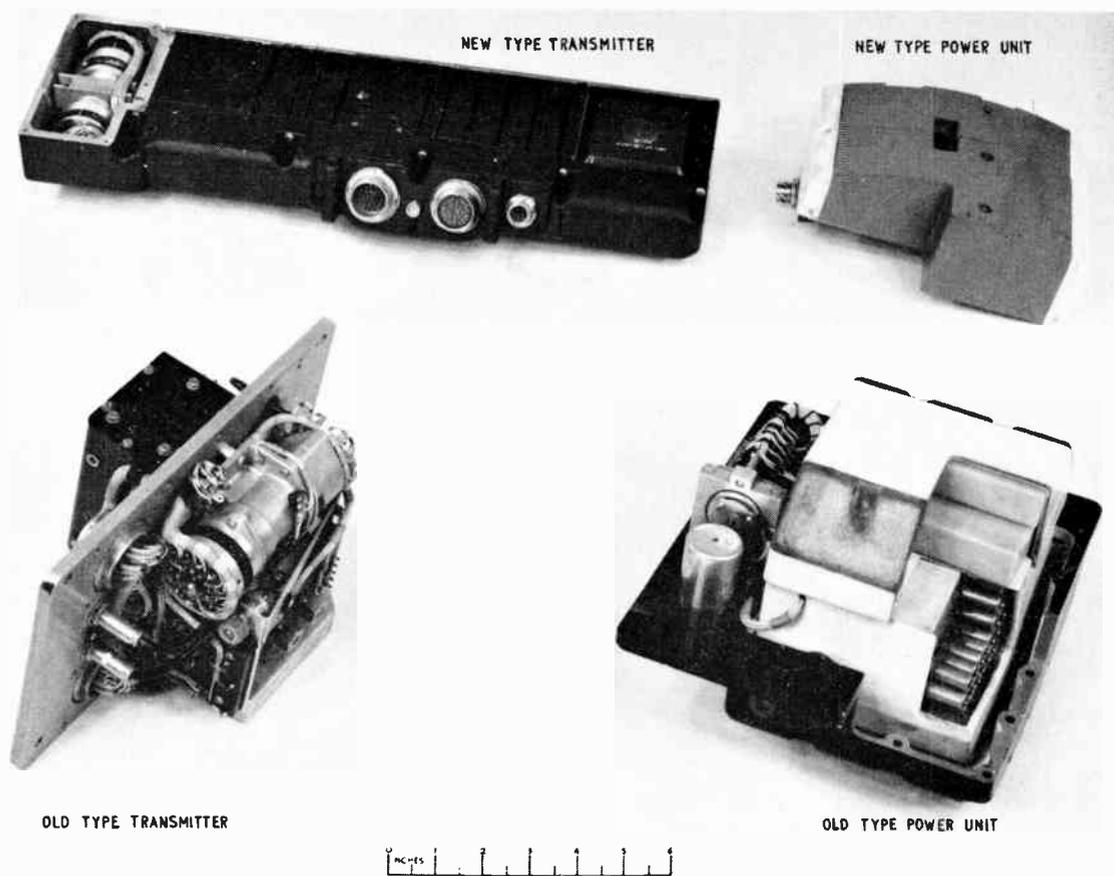
Fig. 3. Illustration of old and new type senders.

An "old style" telemetry transmitter was powered by a number of batteries, providing directly the various supplies required. A set of batteries for a sender was commonly made up of cells of several types whose charging requirements, storage life, permissible operating temperatures, etc., were all different. Nearly all types of cells commonly employed had a working voltage of between 1·1 V and 1·2 V. There was no combination of such cells which could conveniently provide 6·3 V as required for valve heaters.
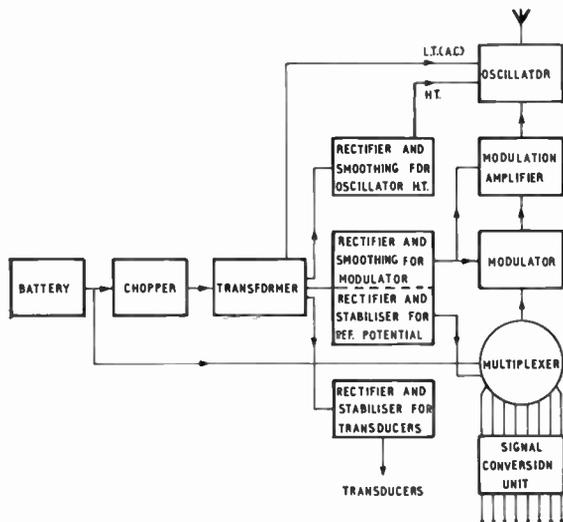
Fig. 4. Block diagram of modular transmitters.

A more elegant solution is currently employed. A single battery is followed by a transistor chopper, a transformer with a number of secondary windings, and an equal number of rectifying, smoothing and stabilizing circuits to provide the supplies required. The r.f. oscillator heater is supplied with a.c. from a winding on this transformer.

It is of interest to note here that, in contrast to common experience, the total power requirement of the transmitter has not been significantly reduced by the introduction of transistors. This is because the familiar mechanical commutation switch and valve r.f. oscillator, which consume most of the power supplied to the equipment, are still employed.

Semi-conductor devices are used where applicable, with the result that the telemetry engineer's greatest problem—that of transients caused by the effect of shock and vibration—has been largely overcome, and has been replaced by the problem of a slow drift caused by the effect of temperature variation on the transistors. The visible difference is that the largely mechanical means for insulating valves from the environment have been replaced by pre-dominantly electrical means of stabilization and feedback. Conventional heat sinks are of course employed but are of limited application in the high ambient temperatures encountered.

It is no coincidence that this modular sub-unit form of construction has been introduced concurrently with a widespread use of semi-conductors. The d.c.-a.c.-d.c. conversion technique presently employed to obtain transmitter supplies could have used valves, but the convenience thus obtained would have been over-ridden by the poor efficiency and reliability, and the large size, of such devices. Direct battery supplies were always used for this reason and the transmitter contained only three or four sub-units (multiplexer-modulator-oscillator and sometimes signal conversion unit).

It was only with the introduction of transistors that convertors were worthy of consideration. Use of such convertors increased the amount of circuitry available for division into sub-units. The gains achievable by the use of numbers of common sub-units would have been largely offset had they not been designed for economical use of space and convenient replacement.

3.2. Description of Sub-Units

3.2.1. The chopper and transformer

These two units shown in Fig. 5 are best described together. The connections between these two units and to the power supply, which are all made via the unit base plugs, are as shown in the figure. The two units then form a conventional d.c.-a.c. inverter working at approximately 400 c/s. The diode ensures that the circuit is always unbalanced when supplies are switched on, so that oscillation will always start. The same chopper unit is suitable for power requirements from 5 to 75 watts from any commonly used supply
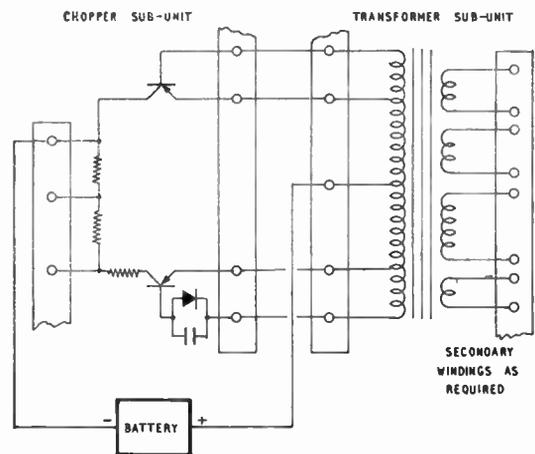
Fig. 5. Circuit arrangement of chopper and transformer.

voltage. The transformer used depends on the precise requirements of the transmitter and several standard varieties exist. The conversion efficiency of this arrangement is not less than 80%.

3.2.2. Oscillator h.t. supply unit (Fig. 6)

The output of an appropriate secondary winding on the transformer is rectified by the bridge-connected
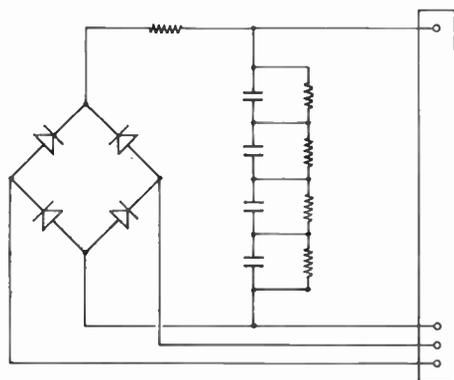
Fig. 6. Circuit diagram of oscillator h.t. supply unit.

diodes and smoothed by the R-C network. Series connected, low voltage capacitors are used purely to ease the task of packing them into the module can. The unit is suitable (with appropriate input from the transformer) for any h.t. demand up to 400 V at 150 mA.

3.2.3. Modulator and reference potential supply unit (Fig. 7)

This consists of two separate units within the same container:

(a) Modulator supply: A ±12 V supply is required for the modulator, and when the larger r.f. oscillator is in use this unit is also called upon to supply power to the modulation amplifier. The range of load current to be supplied is therefore high, but great stability of output voltage is not required since the modulator incorporates stabilizing circuits. It is thus sufficient to rectify and smooth this input from the transformer as shown and adjust the output voltage to ±12 V on load by means of the variable resistors.

(b) Reference potential supply: High stability is required at low current and is obtained by use of a Zener diode. The output voltage is adjustable by means of the variable resistance to the value required for any particular application.
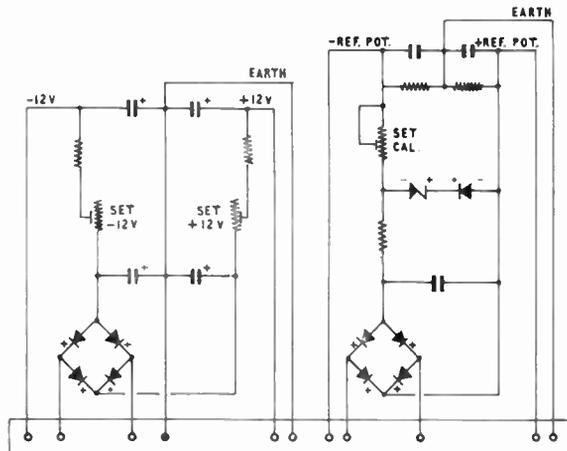
Fig. 7. Circuit diagram of modulator and reference potential supply unit.

3.2.4. Transducer supply unit (Fig. 8)

A highly stable output is required at an accurately known voltage, to supply transducers varying in number and resistance in each application.

A change in the load during flight, caused for example by a transducer becoming open circuit, should ideally cause no change in the output voltage. The output of the unit must accordingly be well stabilized against both input voltage variation and output current variation. A fairly complex circuit arrangement is required to give a performance approaching that provided by direct battery supply.

The d.c. obtained from the bridge rectifier and stabilized by Zener diodes is further stabilized by a series stabilizer controlled by a differential error amplifier. Two standard varieties of the unit are available for output voltages of $\pm 1\frac{1}{2}$ V and ± 3 V respectively.
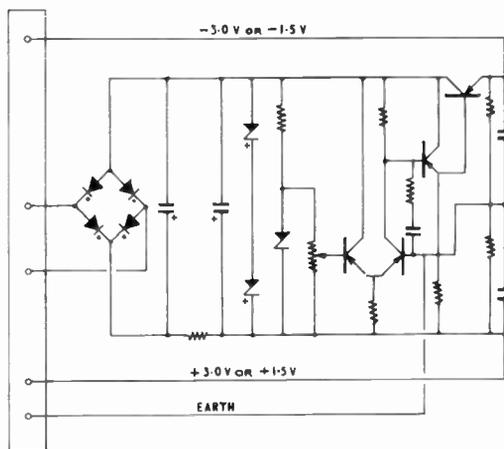
Fig. 8. Circuit diagram of transducer supply unit.

3.2.5. Signal conversion unit

This is invariably special to each application. It is conveniently made up, using standard piece parts, in modular form.

3.2.6. Multiplexer (Fig. 9)

This unit is the exception to the modular rule. Rotating machinery is basically of cylindrical section.
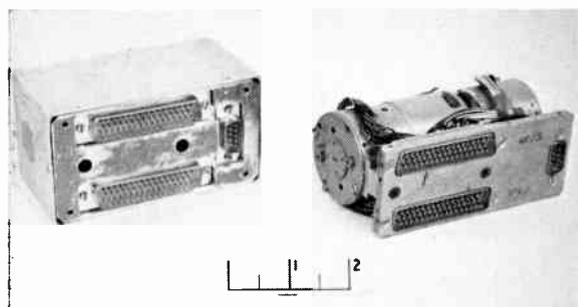
Fig. 9. Photograph of multiplexer.

Advances in this unit relate rather to reduction in size, improvements in commutation and the provision of a plug on the base to ease servicing.

3.2.7. Modulator

The basic requirement is an output of which the frequency depends upon the voltage input. A number of circuit arrangements is possible, for example:

(a) An oscillator involving feedback via a transformer, the frequency being controlled by d.c. current in a third winding on the same core. Although theoretically sound, practical difficulties ensue in an attempt to stabilize the operation at very low and very high temperatures with the same circuit values, as required for a standard unit. This has led to a further development.

(b) A transistor multivibrator circuit, frequency controlled by the base voltage. To achieve the high input impedance required the oscillator is preceded by an emitter-follower chain, and is
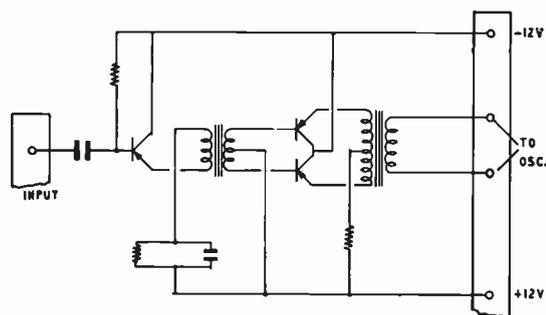
Fig. 10. Circuit diagram of modulation amplifier.

followed by an amplifier to raise the power level to some 300 mW.

3.2.8. Modulation amplifiers (Fig. 10)

The output of the modulator is insufficient for direct application to some oscillators. Rather than increase the size of the modulator, an amplifier has been built into a separate unit, which can be omitted from the transmitter when not required. This unit consists of a current amplifier, transformer coupled to a push-pull Class B amplifier which in turn is transformer coupled to the oscillator grid.

3.2.9. Oscillator (Fig. 11)

The oscillator illustrated bears a family resemblance to those previously described† in that it uses an earthed-grid Colpitts circuit. The construction, however, is somewhat different. Most of the space within the modular dimensions is occupied by a block of light alloy, in which are bored three holes in the vertical plane (with the unit standing upright). One hole contains the valve, while the anode and cathode tuned circuits are made up of lumped capacitance and the distributed inductance of the coaxial lines formed by the other two holes and rods passed centrally through them. Heat loss from the block assists to cool the valve, while the whole structure is strong and ably withstands the rigours of its environment. The rated output is 0·5 W.
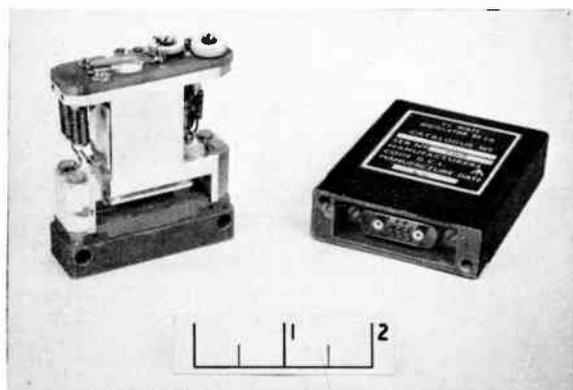
Fig. 11. Photograph of oscillator.

An oscillator for longer range applications to give an output of 6 W is in the course of development.

3.2.10. Units for special applications

Events which occur only once during a flight and then for a short period, are of special interest. The bandwidth required to telemeter these events is often such that the entire capacity of a transmitter has been

† Rae, loc. cit.

employed to monitor them. This is wasteful; the transmitter sends no information except for a very short time, and another transmitter is used to convey the more ordinary signals. A more economical method is to switch the transmitter from its multiplexed input to an input from the special signal just before it occurs, and back again afterwards. This, of course, can only be done if it is permissible to lose the multiplexed signal for a short time. (It is often accepted as preferable to the alternative, which involves doubling the amount of telemetry equipment carried.)

With the aid of semi-conductors and other small components now readily available the relatively complex circuitry required—fast-switching gates, flip-flops and triggering circuits—may be packed into one or two modular containers. Such specialized units, of which the above is an example, are fast becoming commonplace.

All the components of the transmitter are mounted upon a chassis, which although it is shaped to fit the available space, is basically a plate containing a number of sockets. The wiring between these is completed below the chassis and the units plugged in above. Since all connections to the chassis and the units are by these plugs and sockets they may be tested separately, and at different places at different times. The final assembly of the transmitter is simple and the testing of it little more than a confidence check.

4. Future Trends

Since neither the *Scout* nor the *Skylark* telemetry systems were designed for these particular applications, it is unlikely that they indicate any particular trend of development towards better space research telemetry.

Regarding satellite telemetry it is the opinion of the authors that digital systems will eventually be used. There are broadly two reasons why such views are held. The first is that many of the inputs are in digital form anyway and the tendency even in measurements of electrical quantities is to use counting techniques. The second reason concerns the need for automatic data reduction and analysis. As has already been stated, most of the data telemetered from space research vehicles are liable to require detailed analysis. Because of the large volume and steady flow maintained for many months huge backlogs will inevitably result unless it can be dealt with at a rate more or less equal to the arrival rate. To make this possible will obviously demand the use of digital computers. Even these will not save the situation if preparation of the data in a form suitable for computers is itself slow.

For the above reasons it is envisaged that such quantities which are not naturally in digital form in

a satellite will be converted and all data will then be transmitted via a digital system. Eventually, the digital telemetry system will be designed specifically to work into a digital computer or vice versa.

In the case of space probes like *Skylark* it is likely that U.K. projects will continue to make use of telemetry equipment designed primarily for missile use. Considerable economy results from the use of available airborne equipment and range facilities. The rapidly advancing state of the art indicates that further improvement in missile telemetry will soon be achieved. The improvements are of two main types, namely:

> Improved communication efficiency.
> Smaller airborne equipment.

Improved communication efficiency will largely result from the use of improved solid state devices. Receiver noise figures can be reduced significantly by the use of parametric amplifiers. Transistors capable of v.h.f. outputs in the range 100 mW to 500 mW are now available and transmitters of this kind are now being developed. Transistors capable of greater power output should be available in the near future. A transmitter using transistors can be made substantially free of microphony and therefore direct f.m. can be used instead of f.m./a.m. thus obtaining further increases in communication efficiency. The transistor transmitter is being designed with crystal control and the resultant improvement in r.f. stability permits more simultaneous transmissions in the allocated frequency band and also offers the possibility of improving receiver detection efficiency.

Improved communication efficiency permits a reduction in the size of the airborne equipment and hence an increase in payload. The size reduction results, in the first instance, from the improved communication efficiency in that less r.f. power is required for a given performance and the size of the transmitter and its associated power supplies is reduced. In addition, transistor type oscillators are more efficient in the conventional sense of the ratio between power output and power input and further size reduction results.

The improved reliability of semi-conductors can result in space saving which is comparable with that due to the reduced size of the individual components. The reason is as follows. In explaining the philosophy of the present module system, two key points were ease of servicing and the ability to assemble the modules into various shapes. If the transmitter is small enough its shape need not be variable. If the equipment is reliable enough it need not be sub-divided for ease of servicing. By making the transmitter (less multiplexer, information unit and battery) in one block, all the space occupied by plugs, sockets and cable runs of the
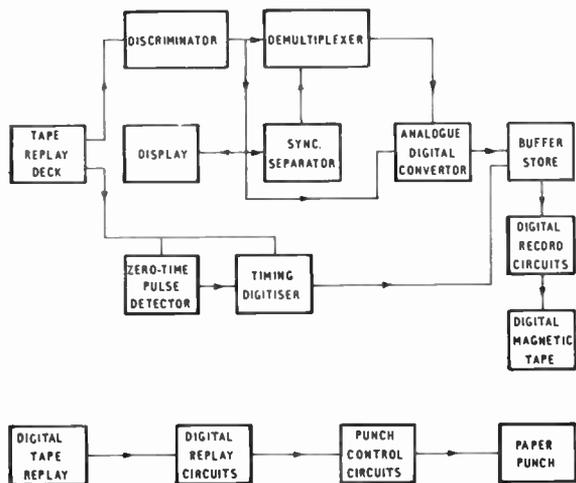
Fig. 12. Simplified block diagram of data reduction equipment.

module system could be saved. This would result in a very small assembly.

5. Data Reduction

As has been mentioned previously, the data reduction equipment now to be briefly described is a necessary link between the telemetry output and the digital computer. That is, it is necessary if anything like full value is to be obtained from the experiments carried out in the *Skylark* rocket.

The *Skylark* firings take place in Australia, where one form of recording uses magnetic tape. The subcarrier is detected, reduced in frequency by 95 kc/s from the range 130–160 kc/s to 35–65 kc/s and recorded on one track of the magnetic tape. Other data, including time in coded form and reference signals, are recorded simultaneously on other tracks of the same tape. Copies of these tapes are made available to experimenters in the United Kingdom who need to reclaim, reduce and analyse the recorded data.

A simplified block schematic diagram of the reduction equipment is shown in Fig. 12 and a sketch of the complete equipment is shown in Fig. 13.

The tape is replayed into a frequency discriminator to produce a voltage output of the same form as the original input to the frequency modulator in the sender. This waveform is fed to a fast analogue-to-digital converter and also to a synchronization pulse detecting circuit.

The synchronization pulse is used to generate a series of strobe pulses which are used for two functions. Either they are used to form 23 gates through which the original analogue inputs can be recovered;

or they can be used to operate the analogue-to-digital converter, the output of which is the original data in an 8-bit binary form. These are passed to a buffer store and eventually recorded on another magnetic tape. The recording is in parallel form across the tape, one bit on each of eight tracks.

At the same time as data are being replayed from one track, time to millisecond accuracy is taken off another, zero time being a special pulse called the "zero time pulse". Time is digitized and recorded on the same tape as the data in the place originally occupied by the synch.-pulse. Only one time is recorded for each telemetry frame and that is the time of arrival of each synch.-pulse. To obtain the time of a particular data sample it is necessary to interpolate and this is a subsequent computer operation.

Full scale and zero calibration references are mixed in with the data and these are treated exactly the same as data points.

The application of these references to correct the data is another operation left to the computer.

A display is provided so that the discriminator output can be observed during operation. By using the synch.-pulse the display is locked to the rotational speed of the multiplexer in the sender.

At the present time, the computer which will be used by the experimenter requires a punched paper tape input. It is therefore necessary to replay the digital tape at reduced speed so as to produce another recording on punched paper tape.

As can be seen on Fig. 13 showing a sketch of the equipment, it will be housed in four standard 6 ft racks. This includes the power supply and two spare trays which will leave room for later development.
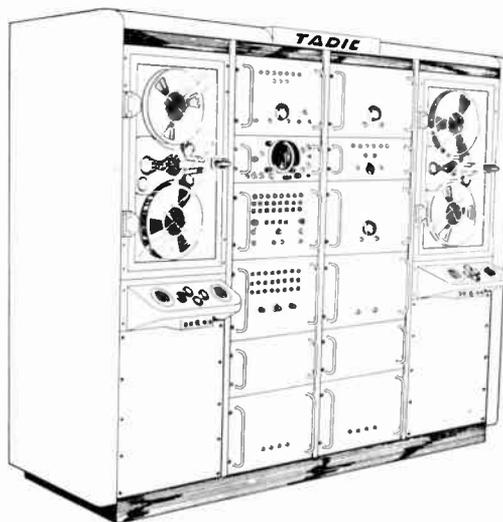
Fig. 13. Sketch of complete data reduction equipment.

Part 2: Comparison of *Scout* and *Skylark* Telemetry Systems

6. Introduction

The *Scout* system including the telemetry will be American, although the experiments and the experimental equipment will be British. Hence, much of the detailed technical information concerning the telemetry system is not available in the United Kingdom.

However, basically, the systems used in *Scout* and *Skylark* are the same.

Scout uses a modified version of that used in *Explorer VIII*. The modifications which have been made have resulted in a severe range problem. The way in which this problem arose and the fascinating solution found are now discussed.

7. General

Scout and *Skylark* are both used for space research but the information gathering potential differs in the two cases. *Skylark* has a life measured in minutes and all the measurements will be made at the same latitude and longitude but at various heights up to 100 miles or so. A satellite however, will have a life measured in months. It will circle the Earth about sixteen times per day and will therefore be collecting data from many positions of longitude and latitude.

Another difference is in the numbers of rounds used or planned. There are only three of the *Scout* series of satellites planned and these will cover a period of about three years. On the other hand, *Skylark* rockets have been in use since February 1957 and to date about thirty have been fired with telemetry installed.

In view of these differences it is not surprising to find significant differences in the telemetry equipment. Some of these spring from the need for longer life and high long term stability requirements of satellites and the need for relatively cheap, small and yet reliable telemetry for missiles and rockets.

Another area of comparison is data rate. The number of data points transmitted in unit time is higher in *Skylark* than it will be in *Scout*. As a general rule, short life, short-range experiments will always be associated with higher data rates than are long life and long-range experiments since it becomes progressively more difficult to transmit high data rates as the range increases. Also high data rates maintained for long periods will almost certainly result in clogging of the machinery used for data reduction and analysis.

8. Detailed Points of Comparison

8.1. *Multiplexer*

Both the *Scout* and *Skylark* telemetry systems use time multiplex. In *Scout* there are 16 channels and in *Skylark* there are 24. In both cases channels can be sub-commutated to give a higher number of channels of lower information bandwidth.

Although the multiplexers used are functionally similar there are significant differences. The *Skylark* multiplexer consists of a 24-segment commutator having a wiper driven by an electric motor. The *Scout* multiplexer consists of individual electronic switches controlled by a series of binary dividers and an electronic clock. The more significant performance differences of the two devices are:

(a) Good switching action is characterized by low and constant forward resistance, very high back resistance, low noise and low contact potential. In these respects, the mechanical switch is much superior to the electronic switch.

(b) The rubbing action of the mechanical switch gives a relatively short service-free life. The precise value depends on many factors such as rubbing velocity, but a typical figure for high-speed switches is 100 hours. This is quite suitable for missile work but useless for satellite work. The solid state electronic switch can have a life comparable with that of the satellite.

(c) The size and complexity of the mechanical switch increases slowly as the number of channels increases, since a segment is a small part of the complete assembly. The size and complexity of the electronic switch increases in about direct proportion to the number of channels since the number of components per channel is roughly constant.

(d) The speed of the electric motor in the mechanical switching is influenced by such factors as acceleration, power supply and temperature variations. These factors have much less effect on the clock of the electronic switch. This has important system implications since, with rapidly changing sampling rates, a significant part of the data handling capacity must be allocated to the function of synchronization. Even slow changes in sampling rate lead to poor system utilization. Whatever the speed tolerance, the bandwidth of the data must be made compatible with the lower limit and yet the system bandwidth, and hence errors due to noise, must be compatible with the higher limit.

8.2. *Mark-to-Space Ratio*

In both *Scout* and *Skylark*, the multiplexer sequentially samples the input voltages and effectively keys a sub-carrier on and off during each sampling interval. In *Skylark*, the mark/space ratio of the keying action is high (greater than 7 : 1). In *Scout* it is only 1 : 1.

APPLICANTS FOR ELECTION AND TRANSFER

As a result of its meeting on 21st November the Membership Committee recommended to the Council the following elections and transfers.

In accordance with a resolution of Council, and in the absence of any objections, the election and transfer of the candidates to the class indicated will be confirmed fourteen days after the date of circulation of this list. Any objections or communications concerning these elections should be addressed to the General Secretary for submission to the Council.

Direct Election to Member

BENNETT, Arthur James, M.A.(Cantab). *Cambridge.*
HILL, Frank Lawrence, B.Sc. *Mortimer, Berkshire.*
MILLNS, Captain Frederick Leslie, R.N. *Fareham, Hampshire.*

Transfer from Associate Member to Member

GOODMAN, Group Captain John, R.A.F. *Northwood, Middlesex.*
PETERSEN, Ronald George. *Beaconsfield, Buckinghamshire.*

Direct Election to Associate Member

BREEZE, Guy Hemsley. *Tunbridge Wells, Kent.*
DICK, Frederick Morison. *Sanderstead, Surrey.*
GOODIER, Alan Vivian, B.Sc.(Eng.). *Runcorn, Cheshire.*
GRAY, Flight Lieutenant Ronald Kenneth, Dip.El., B.Sc., R.A.F. *Biggleswade, Bedfordshire.*
HAWKES, Commander Geoffrey Arthur, R.N. *Bognor Regis.*
MOSS, Alan William. *Uxbridge, Middlesex.*
MUNDY, John Eric, B.Sc. *Woodford Green, Essex.*
NEWBOLD, Kenneth Anderson. *Jesselton, North Borneo.*
NOYES, John Frederick. *Romford, Essex.*
POVEY, Wilfred Jack. *Rochester, Kent.*
SQUIRE, Geoffrey Walter. *Stevenage, Hertfordshire.*
TAVENER, Albert. *Barnet, Hertfordshire.*
THOMAS, Alan John. *Chelmsford, Essex.*
TRIMMER, Alfred Lewis. *Stevenage, Hertfordshire.*
WELLDON, Sydney. *Stanmore, Middlesex.*

Transfer from Associate to Associate Member

DAVIES, John David. *Rainford, Lancashire.*
SHAH, Major Saleem Ullah, E.M.E. *Lahore, Pakistan.*

Transfer from Graduate to Associate Member

FOGARTY, Michael John. *Rochester, Kent.*
HUGHES, Raymond. *Hounslow, Middlesex.*
KHATRY, Krishna Bahadur. *Patan, Nepal.*
KNIGHT, Peter. *London, W.C.1.*
LEAK, Malcolm Saunders, B.Sc. *Chelmsford, Essex.*
McINTOSH, David John, B.Sc. *St. Albans, Herts.*
MEARNS, James Robert. *Hayes, Middlesex.*
REES, Flight Lieutenant Gareth Huw, B.Sc., Dip.El., R.A.F. *Henlow, Beds.*
RYNKIEWICZ, Artur Edward. *Harlow, Essex.*
TRIFFITT, David Pressley. *Romsey, Hants.*

Transfer from Student to Associate Member

BRENDISH, Stewart Morris Norman. *Stanmore, Middlesex.*
DONALDSON, Colin. *Colchester, Essex.*
HATFIELD, John Keith. *Chelmsford, Essex.*

Direct Election to Associate

GOULT, Squadron Leader Bernard Leslie, R.A.F. *Twickenham, Middlesex.*
MALSTER, John. *St. Albans, Hertfordshire.*
OSBOURNE, David Alan. *Romsey, Hampshire.*

Direct Election to Graduate

*ACKUN, Jacob Kobina. *Accra, Ghana.*
ADAM, Thomas Wilkie. *London, S.W.18.*
ALI, Bagh. *Surbiton, Surrey.*
ALLEN, Rodney David. *Reading, Berkshire.*

Direct Election to Graduate (*continued*)

ARTHUR, Brian Charles. *Hayes, Middlesex.*
ASHE, David Arnold, B.Sc. *Wellington, New Zealand.*
ATKINSON, Peter, B.Sc. *Letchworth, Hertfordshire.*
BANFIELD, Brian Walter. *Maidenhead, Berkshire.*
BECKET, David William. *Southampton, Hampshire.*
BOWEN, Gerald Sidney. *Rainham, Essex.*
BROWN, Thomas William. *Farnborough, Hampshire.*
CARTER, Alan William. *Portsmouth, Hampshire.*
CHILDS, Major Peter Desmond R. *Rhosneigr, Isle of Anglesey.*
COFFIN, David Alan. *Liverpool.*
COLLINGE, Peter Dunham. *Rochdale, Lancashire.*
DEAKIN, Peter, B.Sc.(Eng.). *Hounslow, Middlesex.*
DICKINSON, Alan Mervyn. *Basingstoke, Hampshire.*
DONOVAN, Anthony Dominic. *Hemel Hempstead, Hertfordshire.*
DOWNES, Dennis Peter. *London, S.E.7.*
DRAPER, Derrick. *Stevenage, Hertfordshire.*
ELLIOT, Brian Lawrence. *Havant, Hampshire.*
EVANS, James Arthur. *South Ruislip, Middlesex.*
FERGUSSON-NICOL, Alexander Emeric. *Salford, Lancashire.*
GREATREX, Brian Maurice. *Chelmsford, Essex.*
GURNEY, Eric George. *Hemel Hempstead, Hertfordshire.*
HANNAFORD, David Arthur. *Plymouth, Devon.*
HARLOW, Clive. *Stanmore, Middlesex.*
HEATH, Patrick Gordon. *Leigh-on-Sea, Essex.*
HOLDEN, James. *Swinton, Lancashire.*
HUGHES, Kenneth Lawson, B.Sc. *Cradley Heath, Staffordshire.*
JONES, John. *Caerphilly, Glamorganshire.*
LAW, David. *Cheltenham, Gloucestershire.*
McCONVILLE, William George. *Frimley Green, Surrey.*
MACDONALD, John Pert. *Bishopbriggs, Lanarkshire.*
MAY, Richard David. *Chelmsford, Essex.*
MARSHALL, Alan Ernest Thomas. *Colchester, Essex.*
*MUKUTMONI, Flight Lieutenant Manas, M.Sc., I.A.F. *Jalpaigwi, India.*
PALMER, Juan. *Southend-on-Sea, Essex.*
QUAN, Michael John. *London, S.E.5.*
REES, Flying Officer Roderick Alun, R.A.F. *Chippenham, Wiltshire.*
RISHWORTH, Derek George. *Manchester.*
ROBEY, Michael John. *Hayes, Middlesex.*
ROLPH, Denis Dumas. *London, S.E.1.*
SHRUBSOLE, Peter Raymond. *Portsmouth, Hampshire.*
SKEATS, Derek Charles. *London, S.W.11.*
WALKER, Reginald James. *Fetcham, Surrey.*
WARD, John Reginald Gilbert. *Crowthorne, Berkshire.*
WEDD, Maurice William. *Southend-on-Sea, Essex.*
WHITESIDE, Richard James. *Totton, Hampshire.*
WILSON, Tony. *London, S.W.19.*
WILTSHIRE, Deryck Antony. *Stevenage, Hertfordshire.*
YAXLEY, Alan Frederick. *Reading, Berkshire.*

Transfer from Student to Graduate

ALLEN, Patrick Donald. *London, E.18.*
BURTON, Geoffrey. *Abingdon, Berks.*
CHALLIS, Anthony Frank. *Hatfield Peverel, Essex.*
CROMWELL, Richard Arthur. *Tewkesbury, Gloucestershire.*
DOWSE, Peter James. *Chelmsford, Essex.*
GOODWIN, Gerald. *Barrow-in-Furness, Lancashire.*
HARROLD, Ronald Thomas. *Chelmsford, Essex.*
JENKINS, Cyril Victor Beresford. *Pontypridd, Glamorgan.*
JOHNSON, Joseph Frederick C. *Upper Hutt, New Zealand.*
MARSDEN, Norman Wain. *Sheffield.*
MOODY, Robert William. *Burgess Hill, Sussex.*
PEARCE, Roger Frederick. *London, N.W.2.*
TALGERI, Gurudutt Shripadrao, B.Sc. *Bombay, India.*

STUDENTSHIP REGISTRATIONS

The following students were registered at the 26th October meeting of the Committee. The names of a further 31 students registered at this meeting together with 97 students registered at the 21st November meeting will be published later.

AGALA, Melford. *Lagos, Nigeria.*
AMOS, Trevor Harold. *Stamford, Lincs.*
ARNETT, Leslie F. *Great Malvern, Worcs.*
BADGER, Philip Alan. *Wokingham, Berks.*
BAJAJ, Mohinder Singh, M.Sc. *Delhi.*
BAMGBOSE, Nathaniel. *Ibadan, Nigeria.*
BARNES, David William. *Haywards Heath.*
BARNES, Raymond Alan. *High Wycombe.*
BHATTACHARYYA, A. N. *London, N.W.11.*
BROMAGE, Clifford. *Malvern, Worcs.*
BROWN, Edward Ernest. *South Shields.*
BURN, Cyril B. *Hull, Yorks.*
BUTLER, Michael W. *London, S.E.20.*
CASE, Edward N. A. *Stevenage, Herts.*
CHANTLER, Anthony Robert. *Isleworth.*
CHATTERJI, Jagan N., M.A. *Kanpur, India.*
CHINASING, Sean C. *Trinidad.*
CLARE, Gordon L. *Thurso, Caithness.*
CRAIG, Donald K. *Heston, Middlesex.*

DONNITHORNE, Norman Guy. *Anglesey.*
DUNCAN, Alexander R. *Weston-super-Mare.*
EGWU, Godwin. *London, N.5.*
EVANS, David Stuart. *Reading, Berks.*
FENLON, Dennis S. *Bromley, Kent.*
FOSTER, Donald. *Southport, Lancashire.*
GALLON, Albert E. *Church Stretton, Shropshire.*
GILL, Allan. *London, W.7.*
GOH TONG CHYE. *Singapore.*
GOODMAN, Matthew Percy. *Ilford.*
GREENLAND, Elwyn. *Luton, Bedfordshire.*
GREINIG, Allan E. *Leatherhead, Surrey.*
GUPTA, Chandra Pal. *Bombay.*
GURNEY, John H. P. *Ledbury, Herts.*
GUY, Derek G. K. *Luton, Beds.*
HERONNEAU, Roy. *Hull, Yorks.*
HOLT, Alan James. *Malvern, Worcs.*
HOWARD, David William. *Corsham, Wilts.*
HUNTINGFORD, Frank. *Worcester Park*

JAMES, Brian M. *London, S.W.19.*
JONES, David Evan. *London, S.W.9.*
JONES, Richard. *Southend-on-Sea, Essex.*
KALU, Ukwen. *Bletchley, Bucks.*
KENNY, Brian. *Burnley, Lancs.*
KHIN, Maung P., B.Sc. *London, S.W.16.*
LAWSON, Philip J. *Hatch End, Middlesex.*
LIM BENG LEE. *Kuala Lumpur.*
McCALL, Stanley. *Montreal.*
McCALLUM, John Robert. *Cambridge.*
MALIK, Brij B. *Wembley, Middlesex.*
MANN, Malcolm McDonald. *London, W.12.*
MATHEW, Puliyelil G., B.Sc. *Kerala, India.*
MENZIES, Malcolm Raymond. *Stevenage.*
MIR, Iftikhar A., B.Sc. *Lahore.*
MITTAL, Satish C., B.Sc. *Agra, India.*
MORGAN, Hywel Gwyn, B.Sc. *Crawley.*
MORMAN, Andrew R. *Paekakariki, N.Z.*
OGUNMODEDE, Bankole O. *Ibadan, Nigeria.*
OO SAW HLA, B.Sc. *London, S.W.1.*

*Reinstatements.

Radar Investigations of the Upper Atmosphere

By

J. S. GREENHOW, Ph.D.†

AND

C. D. WATKINS, Ph.D.†

Presented at the Convention on "Radio Techniques and Space Research" in Oxford on 5th–8th July 1961.

Summary: This paper is concerned with the measurement of the ionization occurring in the upper atmosphere, using ground based techniques, with particular reference to the aurora and the incoherent scattering of radio waves from the ionosphere. The radar transmitters to be used in conjunction with the two 25 m parabolic reflectors at the Royal Radar Establishment are described, and some of the experiments which will be carried out are discussed.

1. Introduction

Although notable advances have been made in the study of the upper atmosphere through the use of artificial satellites and sounding rockets, there are still a number of measurements which can be carried out more satisfactorily using ground based equipment. This is particularly the case when it is required to make systematic diurnal and seasonal observations from one point on the Earth's surface, of a phenomenon which varies with latitude and height. Some obvious examples are the use of high power transmitters with

large aerials to study ionization effects, such as the aurora and the incoherent scattering of radio waves from the ionosphere.

The R.R.E. interferometer at Defford (Fig. 1), which consists essentially of two 25 m diameter steerable parabolic reflectors capable of operating at
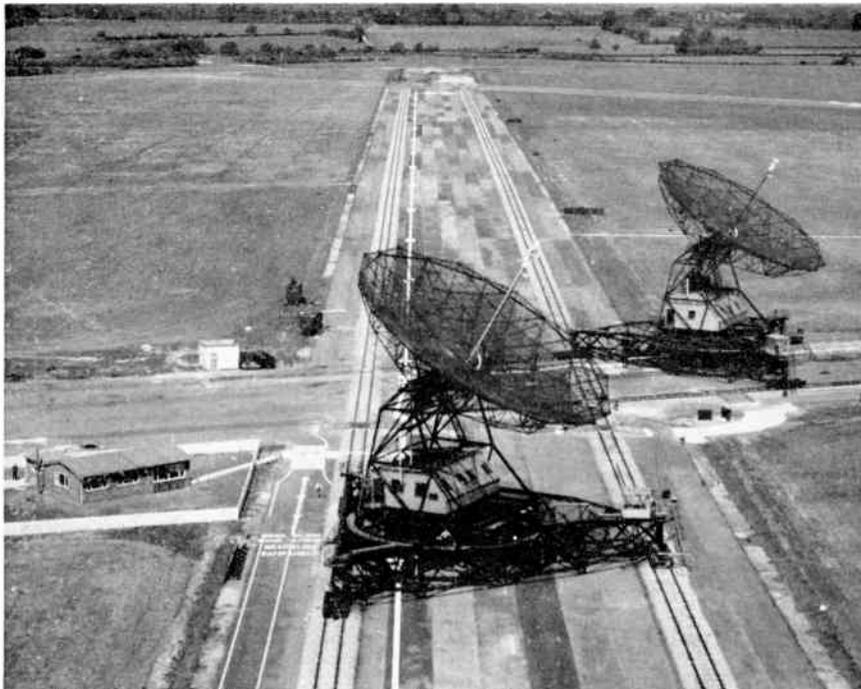
(Crown copyright reserved)

Fig. 1. The radio interferometer aerials at Defford near Malvern.

frequencies up to 3000 Mc/s, will shortly become operational. These aerials will be used for both passive radio astronomy, which is concerned with the reception of radio waves generated in outer space, and active radio astronomy where phenomena comparatively close to the earth are studied by radar methods.

This paper outlines the type of experiments to be

† Royal Radar Establishment, Great Malvern.

carried out using a number of high power transmitters which will be used in conjunction with these aerials, primarily as a tool to investigate the ionization in the upper atmosphere of the earth.

2. Equipment

The parameters of the various radar equipments are given in Table 1. The 1300 Mc/s, 300/500 Mc/s and 32 Mc/s transmitters will be used for simultaneous auroral observations and have already been installed in the aerials. The 32 Mc/s observations will be used primarily to assist in the interpretation of the high frequency results, although some low frequency observations of particular interest will be carried out. The 300 Mc/s transmitter will be used separately to measure the incoherent scattering of radio waves from the ionosphere with a view to determining electron density profiles and ion temperatures.

A very high power 400 Mc/s transmitter is being built at R.R.E. using an experimental klystron developed by S.E.R.L., Harlow; the klystron has been tested but the construction of the transmitter is not yet complete. Because of duplexer problems this transmitter will probably be used with a separate transmitting aerial, using one of the Defford aerials for receiving only. This system has advantages when it is desired to use the video integration techniques to detect very weak signals, for example in the measurement of electron densities at heights of several thousand kilometres using the scattering from free electrons.

Beam type parametric amplifiers will be used at all frequencies (except 32 Mc/s), giving receiver noise factors of the order 1·5 dB.

3. Observation of the Aurora and Incoherent Scattering

3.1. *The Aurora*

The main points of interest in the radar studies of the aurora are: (i) the nature of the reflecting mechanism; (ii) the motions revealed by the echo characteristics; (iii) the relationships between auroral echoes and other phenomena, notably magnetic effects.

It is known that the detection of echoes is closely controlled by the geometry of the magnetic field lines at the relevant heights, the highest probability of occurrence being where the line of sight intersects the field lines perpendicularly (Fig. 2). The full range of available transmitters will be used to study this aspect sensitivity and the wavelength dependence of the echo strengths. Any echoes detected with the highest frequency transmitter would be of particular
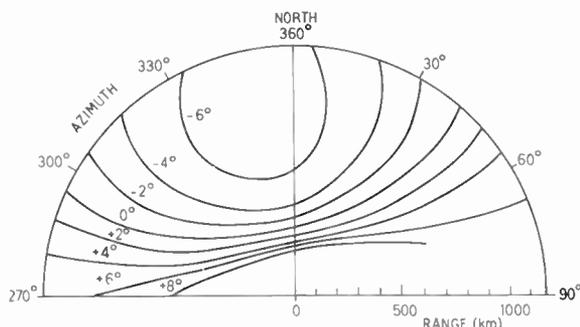
Fig. 2. Curves on the 100 km plane above the Earth showing the off-perpendicular angle ϕ between the line of sight and the Earth's field lines, for a radar situated at Malvern. The maximum probability of detecting an echo should occur at $\phi = 0$, with the degree of possible non-specularity depending upon the length of the irregularities in ionization and the wavelength.

interest and, because of the expected sharp drop in occurrence with increasing frequency, it is likely that integration techniques will be used to increase the overall sensitivity. The integration techniques will also be used with the 32 Mc/s transmitter to study any weak auroral ionization which might occur during comparatively undisturbed conditions. This experiment is relatively important since the expected decline in solar activity during the next few years should result in an increasing number of undisturbed periods.

Auroral echoes reveal motions within the aurora of up to a few kilometres per second. The velocities determined by gross motions of the ionized regions,

Table 1

Parameters of the radars to be used in conjunction with the R.R.E. 25 m parabolic reflectors

	Frequency (Mc/s)	Peak Power (kW)	Pulse Length (μs)	Mean Power (kW)	P.R.F. (pulses/sec)	Full ½ power Beamwidth (deg)	Noise Temp. (°K)
(a)	1300	2500	4·5	3	50 or 250	0·6	250
(b)	300 or 500	100	170	1	50	2·7	200
(c)	32	200	10 to 1000	2	Variable	25	15 000
(d)	400	15 000	200	150	50	2·0	200

however, may not be the same as those measured by Doppler techniques. This problem will be examined by carrying out simultaneous measurements using both methods.

In sub-auroral latitudes it appears that the ionization giving rise to auroral echoes is closely identified with the ionospheric current systems which produce magnetic disturbances. This relationship will be further studied over the wide range of frequencies available and at very low levels of activity.

In recent years, it has been reported that radio frequency noise may be emitted by the aurora. The conditions during which this happens and also the mechanism of emission are far from clear. Attempts to detect such emission will therefore be carried out simultaneously with any radar observations. A useful review of contemporary auroral studies, using radar means, has been given by Booker.[1]

3.2. Incoherent Scattering

3.2.1. Measurement of upper atmospheric ionization and temperatures

It was pointed out by Gordon[2] that the power scattered by free electrons in the ionosphere, although very weak, should be detectable using a high power radar. The first experimental observations of this phenomenon were made by Bowles[3] in 1958 at a frequency of 41 Mc/s, and later observations have been reported by Pineo, Kraft and Briscoe[4] at a frequency of 440 Mc/s.

The magnitude of the effect can be determined by summing the contributions from all the electrons contained in a volume of space defined by the aerial beam and the pulse length, each electron having a back scattering cross-section of half the classical value $4\pi(e^2/mc^2)^2$. Substitution in the radar equation then shows that the received power ε_0 varies in the manner

$$\varepsilon_0 = \frac{kn_e}{r^2} \qquad \ldots\ldots(1)$$

n_e is the electron density and r the range.

k is a constant for a given equipment.[2]

This method therefore enables a direct measurement of the variation of electron density with height to be made. It has the advantage over many other methods that the electron density can be determined both above and below the F-region maximum, and that the derivation of the electron density profile from the observed variation of received power with height is very straightforward.

Theory predicts that the scattered signal should be spread in frequency because of Doppler effects, and that the magnitude of the spread should be of the order corresponding to the velocities of the positive ions at the atmospheric temperature.[5] Doppler shifts of this order are observed in practice; thus in addition to determining values of the electron density this method should also enable ion temperatures to be determined.

3.2.2. Expected echo intensities for the R.R.E. installations

Substitution of the parameters of the equipment (b) in Table 1 in equation (1) shows that for an electron density of $10^6/cm^3$ at a height of 300 km, an echo of intensity 2 dB below receiver noise should be obtained. A receiver bandwidth of 10 kc/s, wide enough to include the expected Doppler spread of 7 kc/s, has been assumed. The electron scattering cross-section
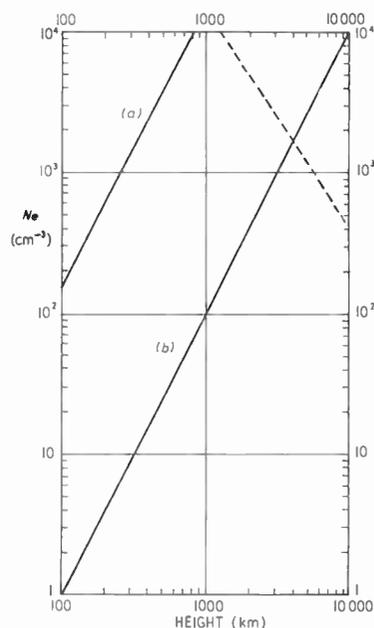
Fig. 3. The electron density N_e, required to give a signal to noise ratio of unity, as a function of height.

Gatewidth, $L = 30$ km; Pulse length, $t = 200\ \mu s$;
Aperture, $D = 25$ m; Bandwidth, $B = 10$ kc/s;
Integration period, $T = 1$ hour; P.R.F. $N = 50$ pulses/s;
Peak power, P (a) = 100 kW, (b) = 15 MW.
– – – – Possible electron density profile.

has been taken as half the classical value, as suggested by theory. It will therefore be necessary to use video integration techniques in order to detect the signal at heights significantly above the maximum of the F-region.

As measurements of diurnal variations in electron density and temperature are of considerable interest, the maximum permissible integration time τ is of the order of one hour (2×10^5 pulses). A series of range gates and integrators have therefore been constructed which enable the total power received in adjacent

range intervals to be compared. Five filters spaced about the centre frequency, followed by integrators, have also been constructed to determine the Doppler spread in the returned signal.

For a gatewidth of 200 μs an integration time of one hour results in an r.m.s. ripple of 0.2% receiver noise between adjacent channels. The signal from the F-region maximum will therefore be about 300 times the r.m.s. fluctuations when the critical frequency is 9 Mc/s. On these occasions it will be possible to determine profiles and ion temperatures up to heights of about 700 km (Fig. 3). During the night and at periods near the sunspot minimum the signal strength may be reduced by a factor of 10.

When the transmitter (d) in Table 1 becomes operational an increase in sensitivity of 22 dB will result. For the same integration time the signal from the F-region maximum will vary up to about 2×10^4 r.m.s. receiver noise ripple, although of course the actual r.m.s. fluctuations between adjacent gates will remain at 0.2% as the signal itself has the characteristics of noise. It should therefore be possible to detect the ionization at a distance of about 3000 km. Alternatively with a short integration time of about 10 seconds, which would still give a signal 1000 times the random receiver noise fluctuations from the region of maximum ionization, short period variations in ionization down to 5% of the background value will be detectable.

In addition to these measurements it might be possible to detect the narrow lines in the spectrum of the scattered radiation, which are separated from the main echo by plus or minus the plasma frequency. The existence of these lines is predicted by theory[5] and at a frequency of 400 Mc/s, near the F-region maximum, they should contain about 10^{-3} times the energy in the main part of the spectrum centred about the transmitter frequency.

4. References

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2. W. E. Gordon, "Incoherent scattering of radio waves by free electrons with applications to space exploration by radar", *Proc. Inst. Radio Engrs*, **46**, pp. 1824–9 November 1958.

3. K. L. Bowles, "Observation of vertical-incidence scatter from the ionosphere at 41 Mc/sec.", *Phys. Rev. Letters*, **1**, pp. 454–5, 15th December 1958.

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5. J. P. Dougherty and D. T. Farley, "A theory of incoherent scattering of radio waves by a plasma", *Proc. Roy. Soc. A* **259**, pp. 79–99, 22nd November 1960.

An Improved Electronic Sector-Scanning Sonar Receiver

By

B. S. McCARTNEY, B.Sc.†

Summary: Although the experimental electronic sector-scanning sonar equipment used in the earlier sea trials (reported in this *Journal* in November 1959) gave good results from the research point of view, and established the soundness of the theoretical studies, it had some serious defects from the practical point of view which showed up markedly when it was used operationally in December 1959 for studies of fish migration. Great improvements in the design have now been effected and are described in this paper. In particular, the use of the "re-modulation" process has enabled the full potential dynamic range of the receiver to be attained.

1. Introduction

Recent papers[1,2,3] have described a type of within-pulse electronic sector-scanning sonar as proposed by D. G. Tucker, and other papers[4,5,6] describe applications of such an instrument.

After initial experimental tests[7] on simulated signals, a set was built and later tested[3] at sea on R.R.S. *Discovery II* under realistic conditions in October 1958, when encouraging results were obtained. The most serious defect reported from this sea trial was the inadequate stability of phase in each receiver channel. Chatterjea[8] investigated the possibility of using a quadrature modulator in each channel in order to avoid the necessity for the tuned circuits which were causing the phase differences. He concluded that such a system, as shown in Fig. 2, would still not be adequate as regards dynamic range.

For further trials, therefore, the original double-modulation system shown in Fig. 1 was retained, using a ladder-type filter of good mechanical construction in place of tuned circuits. This revised scanning sonar equipment was installed on R.R.S. *Discovery II* in November 1959 primarily as a research tool for fishery biologists; useful information was obtained concerning the movement of fish shoals which could not have been obtained with any normal type of echo-ranging equipment. During this second trial it was noted that the stability of channel phase relationships had been improved slightly, but the maximum range of detection was reduced, largely because of the carrier leak from the first modulator. Even when carefully adjusted this proved a serious limitation on the dynamic range available in the receiving equipment.

Further development work on the scanning sonar was, therefore, directed towards improving the stability and increasing the dynamic range of the

receiver. This paper describes the methods proposed for achieving these aims and the reason for choosing a third solution for the modulation problem, termed the "re-modulation" method, which is then described in more detail. Finally results are given of a third sea trial in R.R.S. *Discovery II* in October 1960, when the several modifications were tested with most satisfactory results. For all these trials, the signal frequency was 37 kc/s, the horizontal beamwidth was 1·5 deg, the vertical beamwidth 12 deg, and the scanned sector was 12 deg.
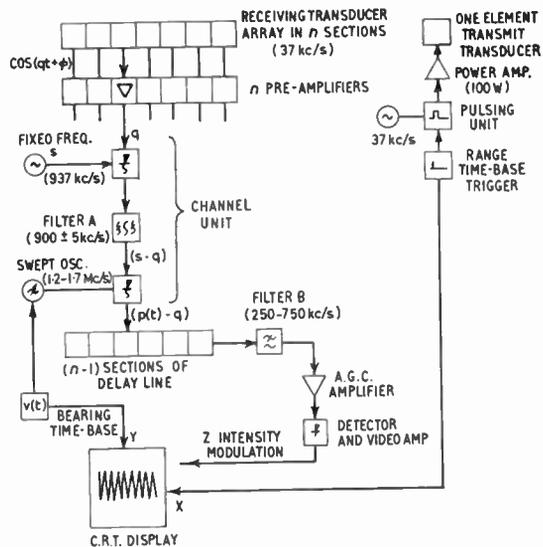
Fig. 1. Electronic sector-scanning with double modulation in the channel units.

2. The Problem of Dynamic Range and Stability

With an ideal noise-free receiver, signal detection would be limited ultimately by reverberation[9]; therefore, in practice, the dynamic range of a sonar receiver must be able to handle reverberation which is just greater than small target echoes at short range

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without overloading, and reverberation which is just greater than ·small targets at long range without it being lost in receiver noise and interference. This range of reverberation levels will vary considerably with the medium conditions as discussed in reference 9; also allowance must be made for signal returns which, though lower in level than the reverberation from that particular range, may yet be detected by pulse-to-pulse, or other methods, of correlation.[10] Thus, estimates of the range of input signal levels vary, but a minimum of 40 dB is expected for horizontal echo-ranging, and nearer 60 dB when operating in calm water over a smooth sea-bed, or ranging vertically downwards. Allowing a margin of 10 dB, this means that the noise introduced by the receiving system must be at least 70 dB down on the overload level.

The principle of scanning the directional pattern of a linear array across a sector, by introducing phase shifts which vary with time, and the method of achieving this by swept-frequency carrier modulation and a tapped delay line have been fully described elsewhere.[1, 3] The noise which is of particular interest with such a system is composed of carrier leak and unwanted sidebands. These determine the lower limit of dynamic range, the upper limit being determined by the overload level.

Since the instantaneous carrier frequency of the signal in the delay line is a measure of the angular position of the receiver beam, one sideband of the swept carrier modulation must be removed. Straight-forward filtration cannot be used, since the frequency sweep of the carrier is greater than the signal frequency (q). The original method proposed to over-come this difficulty was the double modulation system (Fig. 1) which employs a fixed frequency modulation (local frequency s) prior to swept frequency modulation, so that the intermediate signal frequency, $(s-q)$, is greater than the range of sweep, Δf, of the local carrier p; then the unwanted sideband $(p+s-q)$ may be filtered out by filter B. The low signal performance, when this method is used, is limited by the carrier leak, at frequency s, from the first modulation, which is ·performed in the experimental equipment by a transformerless type of shunt modulator.[11] When balanced, the output carrier leak may be as low as 35 dB below the output overload level. However, due to the temperature dependence of the characteristics of the point-contact diodes, this balance cannot be maintained for long periods, so that a figure of 30 dB for modulator dynamic range alone is more realistic. There is a necessity therefore for the filter A in each channel to pass $(s-q)$ and not s, which are 900 kc/s and 937 kc/s respectively in the present system. This gives rise to a high phase slope in the pass band centred on $(s-q)$, so that any variation in component values between channels causes rela-

tively large phase errors and hence distortion of the scanning pattern.

The channel units for the second cruise were redesigned and, as a result, variation due to vibration and temperature changes were reduced, but the suppression of carrier leak was still not adequate. Since the fundamental component of carrier leak has the same phase in each channel, the leak voltages add on a basis of instantaneous values and they therefore appear on the display as a continuous signal at zero bearing at large ranges. Apart from the ensuing loss of signals at zero bearing, the a.g.c. (automatic-gain-controlled) amplifier is controlled by this leak at a fixed gain; signals on all bearings are lost beyond the range at which the peak leak level becomes greater than the reverberation level, which adds on an r.m.s. basis. The power transmitted during the cruise in 1959 was unfortunately only one-third of the nominal design figure due to a mistuning error; this was not counteracted by an increase of gain in the pre-amplifiers until near the end of the cruise. Consequently the effect of carrier leak, which appears after the channel modulator and is therefore not affected by the pre-amplifier gain, was exaggerated and detection was mainly limited to 400 yards for the cruise.
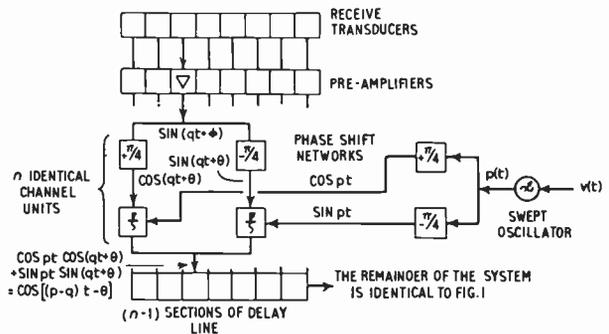
Fig. 2. The alternative system with quadrature modulation in the channel units.

The lower signal limitation when the second method is used (that is, the quadrature modulation system, shown in Fig. 2) was also determined by carrier leak, which is, in this system, a swept frequency and so cannot be filtered immediately. Chatterjea[8] showed that a good carrier balance could only be obtained over a narrow band of frequencies and, with the optimum balance for the whole sweep, the range of signal levels between overload and leak was not better than 28 dB, which is not adequate.

3. Modifications Proposed

The following modifications were put forward as possible solutions to the dynamic range and stability problem.

3.1. Choke-coupled Phase-splitter[1 2]

The transformerless type of modulator used for the intermediate and swept-frequency modulations in the system of Fig. 1 employs a resistive phase-splitter circuit to feed the switching diodes in anti-phase. Some advantage could possibly be obtained by using a choke-coupled phase-splitter, which reduces the effect of grid current, so that the unbalance voltage at the diodes would be reduced for the same switching voltage. Alternatively, with greater pre-amplification of the signal, the carrier voltage could be increased, thereby increasing the overload level, whilst retaining the same leak and hence increasing the dynamic range.

However, there is a significant unbalance voltage due to the anode circuit capacitance at these frequencies and the improvement of 20 dB in the dynamic range quoted for lower frequencies would not necessarily apply. Furthermore, the shunt inductance and stray capacitance of the chokes would need to be identical in each channel otherwise differential phase errors would arise. These could be counteracted to some extent by a phase control inserted in the fixed-frequency carrier input to each channel.

3.2. Range Control of Carrier Voltage[1]

Chatterjea[8] showed that a limited reduction in the carrier switching voltage from its normal value of about 2 volts to 0·5 volt would permit a reduction in carrier leak of about 12 dB, but further reduction in carrier voltage increases the leak by accentuating the difference in diode characteristics. The main objection to this method would be that the full 12 dB would not be usable, because reducing the carrier level to these values reduces the conversion efficiency of the modulator, hence decreasing the output signal level.

3.3. Time-Varied-Gain Pre-Amplifiers

If the dynamic range of signal levels at the receiver due to square law spreading and attenuation with distance could be compressed to 30 dB or less before the first modulator then carrier leak would not be a problem. This may be achieved by varying the gain of the pre-amplifiers with time, and hence with range, either automatically as in the main a.g.c. amplifier or else in proportion to a decaying voltage whose time constant is adjusted to suit the reduction in signal level with range. The amount of compression would not be critical if the present a.g.c. amplifier were used in the common signal path. Automatic gain control for the pre-amplifiers would not be preferred due to the complexity involved and the likely spread of valve characteristics, which would prevent the instantaneous gains of all channels remaining equal over all ranges. This would also apply to the method of applying a time-varying bias to variable-g_m valves, though this would be more flexible in its gain-time
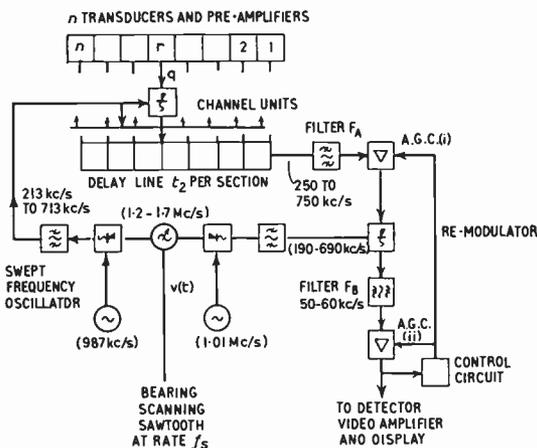
Fig. 3. The receiver with swept frequency re-modulation.

relationship. The best method electrically would be to follow the fixed gain pre-amplifiers by range controlled ganged precision potentiometer attenuators, which would be driven by a motor synchronized to the pulse transmission rate. However the mechanical complexity and cost may not be justified.

3.4. Swept Frequency Re-modulation

If the need for the first modulator can be removed, then not only are the channel units simplified, but also the dynamic range problem is altered in form. At present, the difficulty of attenuating 937 kc/s sufficiently, whilst passing 910 kc/s, and yet maintaining a stable phase characteristic in all channels, is considerable. The re-modulation method described below is a way of reducing the filtration problem to that of passing 50 kc/s to 60 kc/s, whilst attenuating 0 to 24 kc/s in the common signal path only. Except for the delay line, there are now no frequency-dependent networks in the separate channels and this is inherently a more stable arrangement as regards phase relationships. This method was therefore adopted as the most likely solution to the combined dynamic range and stability problem.

4. The Re-modulation Method

A block schematic of the re-modulation method is shown in Fig. 3. It is assumed that the time function which frequency-modulates the swept oscillator is a linear sawtooth, with negligible flyback time. Consider, initially, the input signal to be a continuous wave, of frequency q. The channel unit is now just a single modulator with a swept carrier. The output from each channel consists of one required sideband, one unwanted sideband and carrier leak (which are all swept over a range Δf) and a signal leak at frequency q. After passing through the appropriate sections of delay line and through filter F_A which

(a)

(b)

Output of delay line showing components of rth. channel delayed (r−1)t₂ relative to channel 1

(c)

(d)
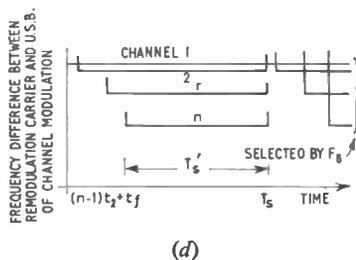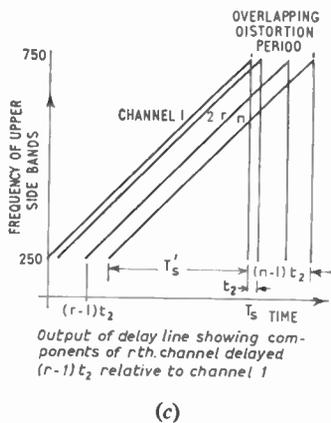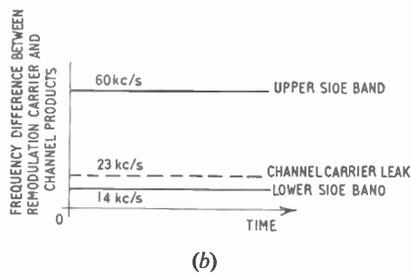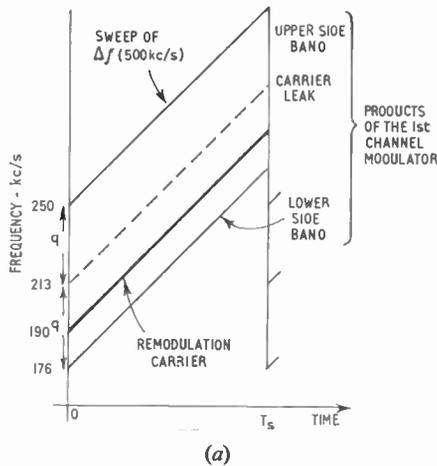
Fig. 4. Time–frequency relations.

(a) and (b) all components, channel 1 only.
(c) and (d) upper sideband only, all channels.

removes the signal leaks the remaining components from each channel enter another modulator, where they are re-modulated with another swept-frequency carrier, the sweep being synchronous with that of the channel carrier, but the actual frequencies being different by a small constant amount. The difference frequencies of this re-modulation are all fixed frequencies and the sum frequencies are filtered by F_B. Since the required signal is separated from the channel carrier leak by a frequency-difference q, and from the unwanted sideband by a frequency difference $2q$, these latter components can be filtered off by F_B too. Now, in the delay line, the frequency of the required sideband is varying linearly with time and the delay line has an insertion phase shift characteristic which is linear with frequency. Thus each component derives a phase shift which varies linearly with time, the rate of variation depending upon the number of section of delay line passed through by that component. Since a linearly varying phase shift is a frequency shift, it follows that the required signal component from each channel will be displaced from that of the next channel by a frequency given by $t_2 \times \Delta f / T_s = f_s$, from Fig. 4, where $t_2(= 1/\Delta f)$ is the delay per section of delay line, and $f_s(= 1/T_s)$ is the scanning frequency. The required signal components in the output of filter F_B are therefore n discrete
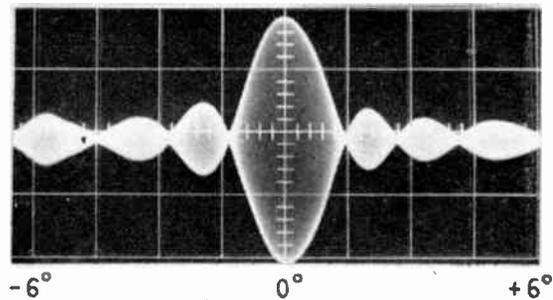
Fig. 5. Scanning pattern for 8 elements-additive.

frequencies spaced f_s apart, which may be filtered from the channel carrier leaks providing $(n-1)f_s < q$. It can easily be shown that the sum of such components is a voltage proportional to

$$\frac{\sin nx}{n \sin x} \cos 2\pi f't$$

where $x = 2\pi(f_s t + (d/\lambda) \sin \theta)$, d is the spacing between each of the n elements of the transducer, λ is the wavelength in water, θ is the angle of incidence of the wavefront relative to the array face and f' is the effective centre frequency of the band of n components. This voltage is the scanning pattern of an n element array at rate f_s and it is shown in Fig. 5 for $\theta = 0$.

4.1. *Requirements for the Band-pass Filter* F_B

It is seen above that the filter F_B must pass n discrete components and reject the other modulation components. However, so far only a continuous input wave has been considered and this must be modified in practice for two reasons. The input actually consists of echo pulses T_p seconds or more long, and also this method of scanning inherently introduces a discontinuity once per scan causing "overlapping distortion". Both these factors influence the actual bandwidth to be specified for F_B.

For optimum signal-to-noise performance the input circuits would have a bandwidth of $1/T_p$, i.e. $1/2T_p$ either side of the carrier frequency q. Instead of n discrete frequencies the output of the filter would then consist of n carriers spaced at f_s with spectra of continuous sidebands extending to $\pm 1/2T_p$ from each one. The total bandwidth B_T must therefore be given by

$$B_T = (n-1)f_s + 2 \times \frac{1}{2T_p}$$

For a within-pulse scanning system $T_p = T_s = 1/f_s$ and hence $B_T = n/T_p$, which is the minimum bandwidth to be expected from information theory, since there are n channels each of bandwidth $1/T_p$.

The foregoing assumes that the required sidebands are n fixed frequencies; consideration of Fig. 4 will show that this is not so due to the overlapping and flyback period when the instantaneous frequency of the component due to the rth channel increases by Δf for a short period $(r-1)t_2$ and is then restored to its previous value. If the spectrum of such an f.m. signal were determined it would consist of many discrete components. But even supposing it were known, it is not easy to say which components are due to the required signal and which are due to the overlapping and flyback distortion period. This approach, therefore, does not lead to a specification for the filter. The overlapping period contains no useful information, and so in principle the output from the array can be suppressed for this period. The problem then becomes one of amplitude modulation of n carrier frequencies with a pulse and a short period $(n-1)t_2 + t_f$ between pulses, where t_f is the flyback time. Superposition of spectra is now valid so a single frequency pulse and its spectrum, Fig. 6, may be considered. To pass this pulse undistorted does, of course, require an infinite bandwidth in theory, but if many of the components of Fig. 6(c) are included then little distortion will occur. In practice it may be sufficient to pass only those components up to the first zeros of

the envelope at $\left[f_r \pm \dfrac{1}{(n-1)t_2 + t_f} \right]$ where f_r is
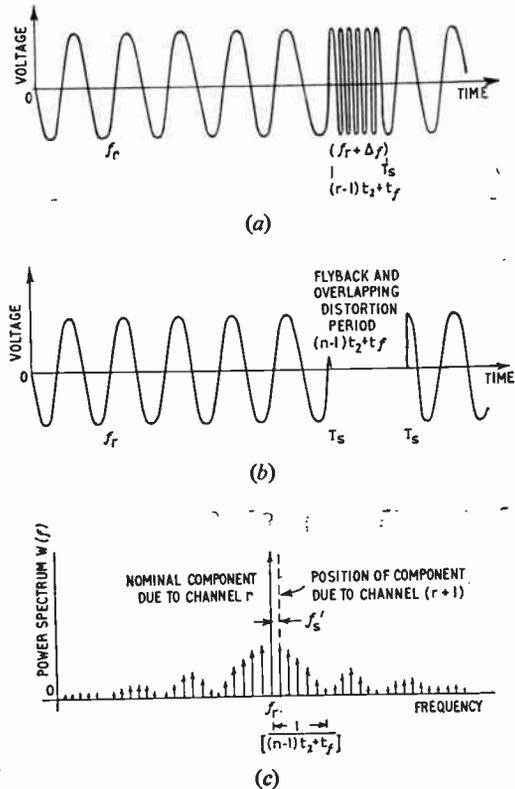
Fig. 6. Waveforms and spectra concerned with 4.1.

(a) Output due to the rth channel after re-modulation.

(b) Output due to the rth channel after re-modulation followed by gating of the flyback and overlapping distortion period.

(c) Power spectrum of (b).

the nominal frequency of the rth channel. The longer the period between pulses, $[(n-1)t_2 + t_f)]$ the narrower this band may be, but then the effective scanning period $T'_s = T_s - (n-1)t_s + t_f$ is decreased and so the effective scanning rate f'_s is increased. Hence the spacing of components due to the n carrier frequencies f'_s apart is also increased. In the practical system under consideration here, $n = 8$, $t_s = 2$ μs, $t_f = 86$ μs and $T_p = T_s = 1$ ms, thus $T'_s = 0.9$ ms giving $f'_s = 1.1$ kc/s. The spread of components due to gating is ± 10 kc/s so that an overall bandwidth of 29 kc/s is required for F_B. The actual filter used had a bandwidth of 24 kc/s and the output, shown in Fig. 5, was sufficiently free from distortion during the forward scan that it could be used without gating.

4.2. *Further Design Problems*

Most of the circuit design is straightforward and self-explanatory and so will not be described here. Only some special details are given below.

(i) The a.g.c. amplifier must be placed between the delay line and the display. The re-modulator and

detector are most efficient when operated over a small dynamic range at a high level so that it would be most convenient to follow filter F_A with the a.g.c. amplifier. However the gain control could not then be obtained from the output of the amplifier itself, since this contains carrier leak from the channels. The gain control could possibly be obtained after F_B but the carrier leak would then overload the re-modulator when the amplifier is at a high gain. A compromise method was adopted and found to be acceptable. The a.g.c. amplifier is divided into halves, the first preceding the re-modulator and the second following F_B. Control for both halves is taken from the output of the second half which consists of signal components only. The first half is preceded by a fixed gain pre-amplifier to make up for the loss in the channel modulators and in coupling into the low impedance delay line.

(ii) The swept-frequency carriers for the channel modulators and for the re-modulator are obtained by heterodyning a sweep of 1·2 to 1·7 Mc/s by two fixed frequencies at 987 kc/s and 1·01 Mc/s respectively. These two frequencies are generated separately using the very stable Clapp-Gouriet circuit.[13] Since the position of the required signal band after re-modulation is dependent upon the difference between the frequencies of these oscillators it is important that the latter are stable. Iron-dust-cored inductors were used with silver-mica capacitors for the tuned circuits, but crystal oscillators would, of course, be preferable. It was found that the slight long-term instability of the pattern was due entirely to these oscillators. Stability of the oscillator frequencies would not be quite so important if the filter F_B had a perfectly flat amplitude response and a linear phase response in its pass band. The slight irregularities are counteracted in practice by initial gain and phase adjustments in the channels; but if the signal band moves across the pass band of F_B then these settings really need to be re-adjusted very slightly.
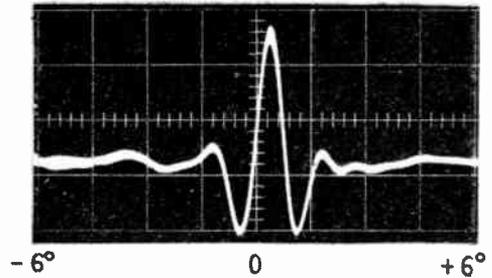
Fig. 7. Multiplicative scanning pattern.

5. Multiplicative Scanning

If the transducer array of n elements is divided into two groups of n_1 and n_2 elements and the added outputs of the two groups are multiplied together, as proposed by Welsby and Tucker,[14] a considerably different directional response (Fig. 7), will be obtained compared with the normal additive response with uniform sensitivity (Fig. 5). The block diagram for multiplicative working is shown in Fig. 8. Each group can be considered to consist of a simple additive system with swept modulation in the channels, addition in the delay line and then re-modulation as described above. The directional response of each group separately is thus scanned across the sector, and in order to scan the directional response due to the combination of the two groups the extra delay line is required. When two similar frequencies are multiplied together the difference frequency component is a unidirectional output voltage whose amplitude is proportional to $\cos \psi$ where ψ is the phase difference between the signals. Here, ψ is a function of time so that an output as shown in Fig. 7 is obtained when $n_1 = n_2 = 4$. It can be seen that the beamwidth is approximately one-half the beamwidth of an 8-element additive array. Also the additive array has side lobe responses after detection which are all positive. The multiplicative system does not require signal detection and the main side lobes, though large, are negative and so do not mark the display. This multiplicative arrangement was successfully tested at sea during the trials in October 1960 and further descriptions and results are given by Welsby.[15]
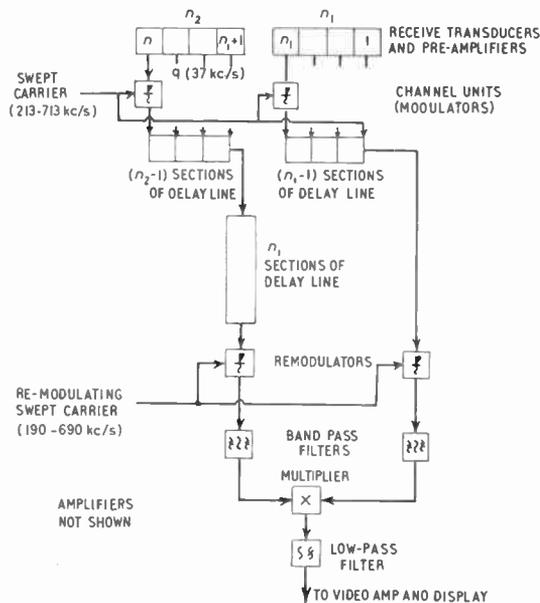
Fig. 8. Multiplicative scanning receiver.

6. Results of the Trials in October 1960

The dynamic range of the receiver for an input injected at the pre-amplifiers was a marked improvement on the dynamic range achieved with the previous double modulation system, as can be seen from the "scanning patterns" shown in Fig. 9. This fact together with increased transmitter power enabled the maximum performance to be obtained from the system. Reverberation was always evident on the display up to 800 yards range and detection was never limited by carrier leak or noise. An 18-in. diameter air-filled steel sphere in mid-water was detected at ranges up to 550 yd in sea depths of 10–20 fathoms, before being lost in reverberation. While being used in conjunction with trials of an interferometric echo sounder in deep water,[16] slopes of the sea-bed were recorded up to 600 fathoms (with vertical beam). (See Fig. 10.)

As expected, the stability of the receiver was very much better than with the earlier equipment. The pattern appeared directly on switch-on and was practically independent of thermal changes.

The most interesting—and fundamental—improvement, however, was obtained by the use of the multiplicative arrangement. The bearing discrimination (tested on an 18-in. diameter sphere) was shown to be twice as good as that of the ordinary additive arrangement. This improved resolution and the lack of spurious side lobe responses for high signal levels make an immense improvement to the quality of the display. This matter is fully reported and illustrated by Welsby.[15]

0 dB

−30 dB

−50 dB

(a)   −60 dB   (b)
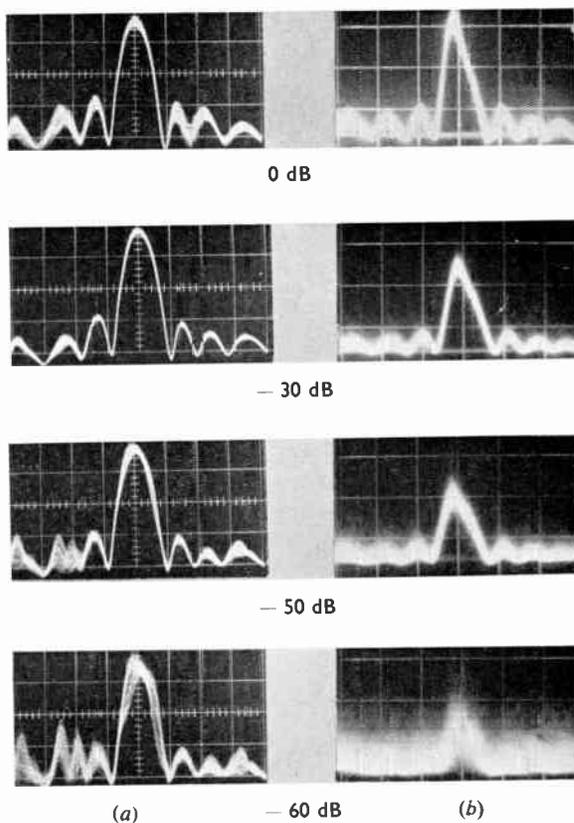
Fig. 9. Comparison of the dynamic ranges of:
(a) the re-modulation system, and
(b) the double modulation system,
with an injected signal at the relative level indicated
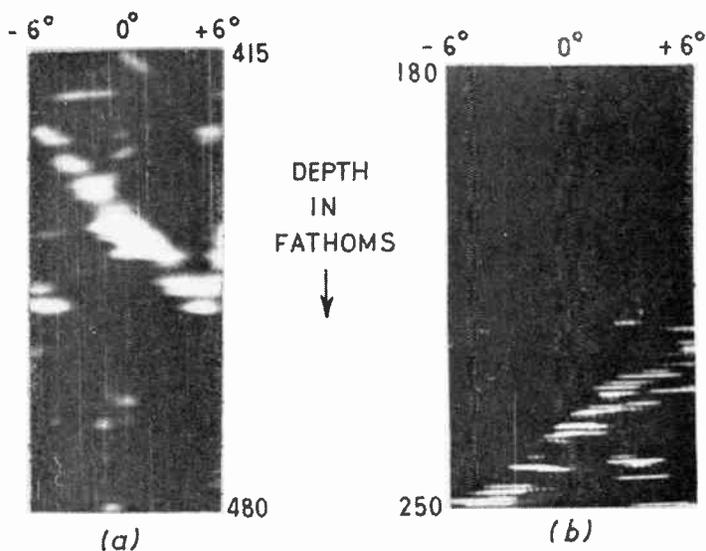
Fig. 10. Display pictures of slopes off the Continental Shelf.
(a) Taken in 1959.   (b) Taken in 1960 (6 channels only).

7. Conclusions

The sea trial in October 1960 successfully demonstrated that the design problems of dynamic range and stability have been solved, for the experimental instrument, by the introduction of the re-modulation method. The circuit complexity in each channel is reduced to a minimum, and this is particularly important for any system which has a large number of channels. The multiplicative arrangement gives almost twice the angular resolution and improved display quality at little extra cost.

It is evident that these modifications would be advantageous for future designs of electronic sector scanning sonar systems using the swept-frequency delay-line principle. Though the requirements of each individual system will pose different development problems, the basic problems common to all may now be considered solved and the design procedure clear.

8. Acknowledgments

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The Tunnel Diode
as a " Solid-state Circuit " Element

By

A. E. BREWSTER †

Summary: The transistor itself is not ideal for use in a truly miniature "solid-state circuit". The tunnel diode as the active element has the desirable feature of low power consumption and is tiny, robust, cheap, immune to surface effects and amenable to mass production. Tunnel diode stages will perform gating and storage functions equivalent to conventional transistor stages, but with greater circuit simplicity, and might therefore be made basic "solid state functional units" in the design of a complete system. It is proposed that the functional units should be separately enclosed in suitably small capsules adapted for association with printed or evaporated wiring networks. Various circuits, such as triggers, a register and gate and serializer, are described to illustrate the application of tunnel diodes to "solid state" and miniaturized systems.

1. Introduction

The ever-increasing complexity of present-day electronic equipment calls for a critical re-examination of methods of circuit construction. Conventional techniques using separate components linked by wire and soldering tags are no longer appropriate. Separate encapsulation of individual semi-conductor devices is both costly and wasteful of space. A typical example of current practice in transistor design uses a silicon wafer having a total volume of only 0.00006 cm^3, yet this is enclosed in a standard case occupying a volume of 0.3 cm^3. Even after due allowance has been made for the problems of manufacture it remains quite ridiculous that each individual semi-conductor element should be surrounded by unusable space to the extent of 5000 times its own volume. The current practice of connecting the collector to the case only aggravates the situation, since the case cannot then be grounded and it often becomes necessary to provide additional space externally in order to prevent spurious coupling between the cases of adjacent transistors. The picture becomes even more depressing when it is remembered that the active transistor structure is significantly smaller than the semi-conductor wafer upon which it is constructed.

An obvious alternative is to manufacture components which are complete functional units in themselves; the so-called "solid-state circuit" approach has already led to the production of tiny flip-flop units containing two transistor elements with their associated circuit components in a single block of silicon. Economically, the attractiveness of this technique would increase with an increase in the complexity of

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the functional unit, which should contain as many active elements as possible and hence reduce the number of external connections to a minimum. However, combination of a large number of active elements into a single unit requires a high order of reliability and conformity to specification in the individual elements if the reject rate of the completed units is to be kept small. Unfortunately the transistor is very susceptible to surface contamination, so some difficulty might be expected in maintaining the performance of a functional unit containing many such elements. An additional limitation on the design of solid-state circuit devices is that, whereas one object of the system is the attainment of very small size, conventional power dissipation figures would cause excessive temperature rise in an otherwise optimum design. Ideally, then, the chosen active element should be of low power consumption and be tiny, robust, cheap, immune to surface effects and amenable to mass production. The tunnel diode is such a device.

2. Typical Tunnel Diode Circuits

In general, the major advantage of extreme miniaturization is to be obtained in digital, computer-type equipment where very large numbers of individual circuit elements are involved. Fortunately these are but a multiplication of a relatively small family of basic functional circuits such as gates and flip-flops. Attention is therefore confined to the tunnel diode as a two-state device and the most elementary arrangement, in which the tunnel diode is loaded by a simple resistor will be considered first.

Figure 1(a) shows a typical tunnel diode characteristic having $i_p = 5$ mA, $i_v = 1$ mA and $V_f = 480$ mV. In the circuit of Fig. 1(b) the tunnel diode is connected in series with its load resistor R1 across a
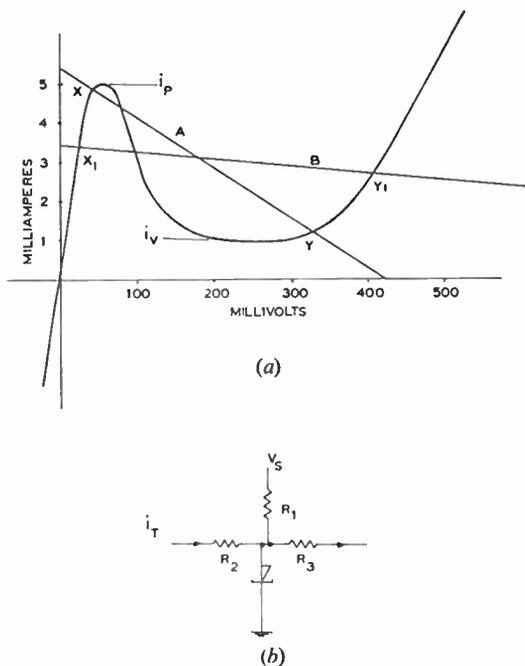
Fig. 1. (a) Tunnel diode with resistive loads.
(b) Elementary single diode trigger circuit.

constant supply voltage V_s. Trigger current i_t may be fed into the junction of the diode and its load resistor, possibly via a resistor R2. The output from the stage might be fed via R3 to drive a further stage. It will be evident that by a suitable choice of values for R1 and V_s the stage may be made equally sensitive to both positive and negative trigger inputs, it being possible in theory to increase the trigger sensitivity indefinitely by placing the load line sufficiently close to the peak and valley current values respectively.

For example, with load line A, representing a value of about 80 ohms for R1, if the circuit is stable at point X it may be triggered to point Y by feeding a current of 200 μA into the trigger terminal. From stable point Y it may be returned to point X by drawing 200 μA from the trigger terminal. Unfortunately, critical trigger sensitivity settings are made unusable by the resulting susceptibility of the circuit to variations in the supply voltage and to small variations of the peak and valley currents with temperature.

Hence if the stage is to be used as a digit store it becomes preferable to achieve maximum stability by keeping the load line as far away as possible from the peak and valley current values. This gives a load line such as B, representing a value of not less than about 1000 ohms for R1 and requiring a supply voltage of about 3 V. In a circuit destined for "solid state" construction this is an immediate disadvantage since, although in the example taken the power dissipation in the tunnel diode will not exceed about 1 mW, as

much as 9 mW will be dissipated in the load resistor. This would be an undesirable cause of excessive temperature rise in a compact assembly.

3. Tunnel Diode Pairs

Where a tunnel diode stage is to be used for a transitory function such as gating, brief storage, or pulse regeneration, there is often no need for a constant power supply, the energizing voltage V_s being applied at the appropriate times by a pulse generator. Such a pulse generator might be required to drive a number of stages simultaneously, so economy dictates that the power demands of the individual stages should be as small as possible; this is a second argument against the wastage of power in high values of load resistance. An alternative is to use a pair of tunnel diodes, connected in series as in Fig. 2(a), as the basic trigger circuit. Here the applied voltage need not exceed 500 mV and the combined power dissipation of the diode pair will be less than 1 mW.

The characteristics and working margins of the twin-diode trigger circuit are shown in Fig. 2(b), where the characteristic curve of one diode is plotted as a load line on that of the other. In the condition shown—with the applied voltage at its maximum— the circuit is able to take up one or other of the stable conditions X and Y. In comparison with the single diode circuit it is more tolerant of supply voltage variations and is less sensitive to spurious trigger inputs. Nevertheless it is possible to combine these features with a very high initial trigger sensitivity, as will now be shown.
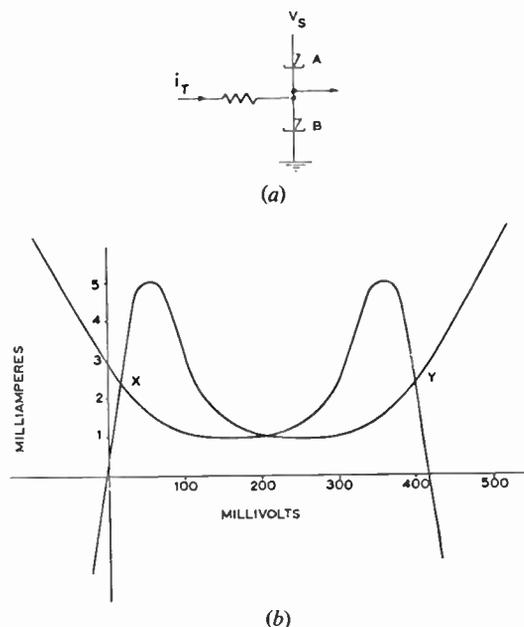
Fig. 2. (a) Twin diode trigger circuit.
(b) Twin diode stable conditions.

Assuming firstly that the trigger current i_t is zero, let the energizing voltage V_s be raised progressively from zero. For negative values of V_s and for positive values up to about 100 mV, both diodes are in a low impedance condition, each presenting an impedance of about 5 ohms. At $V_s = +100$ mV, assuming the two characteristics to be substantially alike, both diodes lie close to their peak currents i_p. As V_s continues to rise in the positive direction both diodes tend to pass round the knee of the curve and enter the negative resistance region. In practice the diode having the lower value of i_p will be the first to do so. Let this be diode A. The total circuit impedance will rise, reducing the series current i. Consequently diode B will fall back to its low impedance region. If the applied voltage stabilizes at $V_s = 410$ mV, as in Fig. 2(b), the circuit will stabilize at a series current of 2 mA, with a voltage drop of 390 mV across diode A and 20 mV across diode B.

As the two diode characteristics are made more nearly identical so the current difference involved in making the choice between A or B becomes smaller. This permits a very sensitive triggering arrangement, since a small additional current i_t may be fed into the common terminal to tip the balance. If i_t is positive diode B will reach the knee first and adopt the higher impedance condition; if i_t is negative diode A will adopt the higher impedance condition.

It is imperative, for a sensitive trigger, that i_t should be present during the rising edge of the applied voltage pulse V_s. However, this is an advantage rather than otherwise since it means that once a given state has been adopted it cannot easily be changed unless the applied voltage is first removed. In practice as little as 100 μA or less is sufficient to trigger a well-balanced pair, whereas several milliamps are required to disturb the condition once established.

4. Compact Forms of Construction

The term "solid state circuit", when strictly interpreted, is understood to mean a device which has been constructed by taking a block of semi-conductor material, shaping it, forming the appropriately doped regions—by diffusion or otherwise—and connecting the appropriate electrodes, so that it is capable of performing a complete circuit function. By this technique it is not possible to construct inductances of any significant value in terms of transistor circuit impedances, and it would be difficult to construct a capacitance of greater than a few hundred picofarads. Hence the circuit to be used must be carefully chosen to be compatible with this method of construction. To this end the tunnel diode circuits here to be described contain tunnel diode elements and resistors only. Nevertheless, since the tunnel diode is potentially able to work in the thousand megacycle region

and has a very low internal impedance, the useful inclusion of capacitance and inductance in such a structure is not unreasonable. As an example, with an early tunnel diode sample an 80 Mc/s oscillator was constructed by tuning the self-capacitance of the diode with an inductance formed by connecting less than 1 cm of wire directly across the tunnel diode element.

To attempt to contain a complete circuit in a single semi-conductor block is not necessarily the best solution. Other techniques, such as vacuum evaporation and microphotography, are capable of producing circuit configurations which are a very significant advance in miniaturization by comparison with soldering tag methods. Such a technique could provide all the L, C and R components, leaving only the semi-conductor devices to be attached afterwards. There would then be little advantage in constructing multiple semi-conductor devices and the opportunity
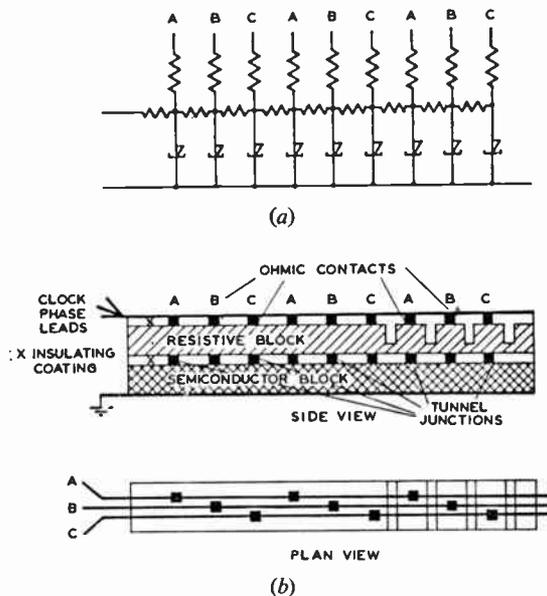
Fig. 3. (a) Three-phase register with single diode per stage. (b) Solid-state circuit method of construction.
If an improvement in current distribution were required the resistive block might be slotted as on the right.

for rejecting faulty individuals would be retained. However, no improvement upon conventional printed circuit methods could be expected so long as the need for good hermetic sealing of transistors dictates the present case sizes. To the tunnel diode this is no problem, since the exposed junction will behave quite normally even when submerged in water. This opens the possibility of dispensing with the protective case altogether, attaching the germanium dice to the prepared circuit board and forming the tunnel junctions in situ.

It is appropriate now to consider some proposed complete structures for existing tunnel diode circuits. Figure 3(a) shows a circuit for a shift register which has been published in the current literature.† Uni-directional signal pulse transference is achieved by using a three-phase clock pulse system; three pulse trains, respectively A, B and C, having a phase displacement of $2\pi/3$ radians, are fed to the appropriate supply terminals. As the clock pulse pattern progresses, from left to right in the diagram, an input signal pulse will be transferred from one tunnel diode stage to the next. Each stage, when it is turned on by its clock pulse, will adopt the condition stored by the previous stage and will in its turn trigger the following stage into the same condition. If the clock pulse progression is arrested the signal pulse pattern will become stationary in the register. Three tunnel diode stages are required to store and transfer each digit of the signal pulse pattern. This three-phase transfer principle is well known and will not therefore be described in greater detail.

This register circuit as a "solid state" structure might take the form shown in Fig. 3(b). A particular feature here is that the complex array of load and coupling resistors may be interpreted as a single block of resistive material, the various current paths being determined by the positioning of the clock pulse electrodes. Since the tunnel diodes are returned to a common terminal it is also possible to form the required number of tunnel junctions on a single block of semi-conductor material.

In the preferred register circuit of Fig. 4(a), using tunnel diode pairs, the situation is more difficult, since in the top half the tunnel diodes have no common terminal and it would seem to be necessary to use separate dice. However, it is of interest to note that where the clock phase electrodes are placed in succession along a uniformly resistive block the phase pattern need not be considered as progressing in steps, but rather as a succession of voltage waves passing steadily along the block. This is exactly equivalent to the manner in which a three-phase alternator produces a uniformly rotating field. Furthermore, the use of three stages per digit in the register is a minimum figure only, and any greater number of stages per digit might equally well be used. The only objection normally would be the increased cost of including the additional stages, but in the present case this approach gives rise to some intriguing possibilities.

If, in Fig. 3(b), the many tunnel junctions are substituted by a single junction extending the full

† I. A. Lesk and J. J. Suran, "Tunnel diode operation and application", *Elect. Engng* (*N.Y.*), **79**, p. 276, April 1960 (Fig. 11, *b*).
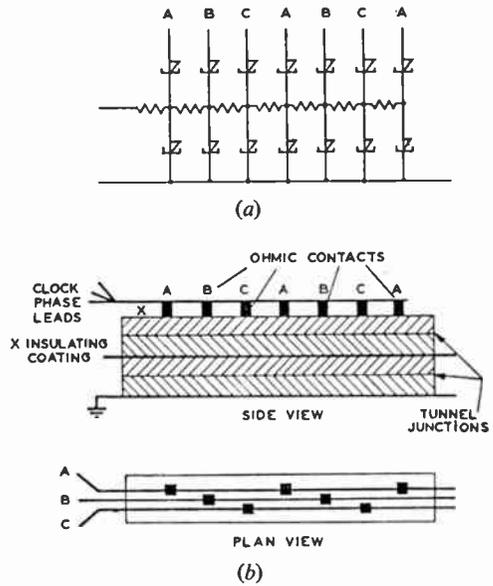
Fig. 4. (*a*) Three-phase register with two diodes per stage. (*b*) Solid-state circuit method of construction.

length of the block, the register might be treated as having an infinite number of stages. The number of signal digits capable of being stored in a given length of register would remain equal to the number of groups of three clock phase electrodes and each signal digit would be carried along on the crest of a clock voltage wave.

By similar reasoning it would become possible to use the circuit of Fig. 4(a), in the structure shown in Fig. 4(b). However, one essential requirement in both cases is that, in order to preserve the integrity of adjacent signal digits, the signal path must be resistive along its length, of the order of a few hundred ohms per digit. Hence in order that the low resistivity semi-conductor blocks should not simply short-circuit the register, it would be necessary to make the device very thin across the tunnel junctions, so that the digit interval might be large by comparison.

A highly speculative extension of thought in this direction suggests the possibility of making a loss-free transmission line. If a number of tunnel diode pairs are distributed equidistantly along a properly terminated transmission line, as in Fig. 5(a), a sinusoidal waveform fed into the "clock" line will set up a travelling-wave pattern which could provide the correct clock phases for the successive stages. It would be necessary to add a d.c. component to make the waveform unidirectional in polarity. From Fig. 5(b) it will be seen that given a clock wavelength λ the element spacing should preferably not exceed $\frac{1}{4}\lambda$. A train of signal pulses fed into the trigger line in phase with the clock waveform would be treated as in the register just described; each signal digit would
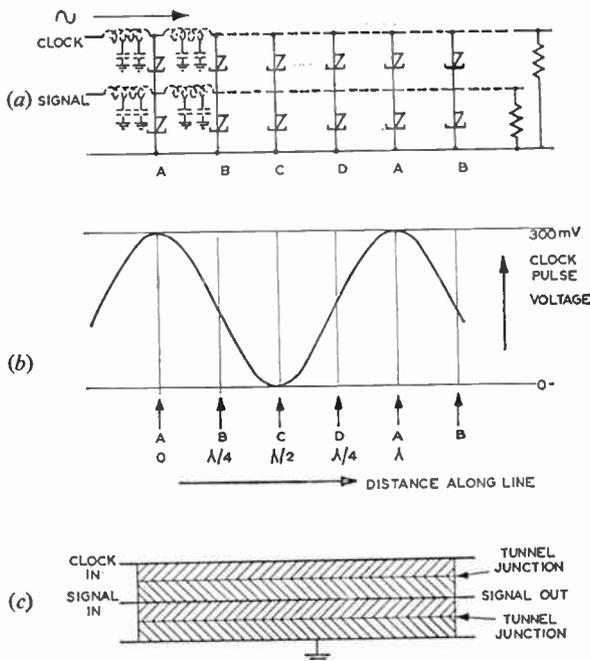
Fig. 5. (a) Transmission-line register.
(b) Clock line waveform.
(c) Solid-state line.

be locked in phase to a positive peak of the clock waveform and would be corrected in both phase and amplitude as it passed each tunnel diode pair. Inevitably the clock waveform itself would require regeneration in an extended length of line, but this would be relatively simple compared with the problem of regenerating the complex and unpredictable signal waveform.

At present this proposal is just an interesting possibility; practical realization of the scheme would require attention to a number of problems. For example there would be the difficulty of maintaining a suitably low clock source impedance to ensure stability in the tunnel diode stages; the characteristic impedance of the line would need to be very low. Also, since the tunnel diode stages would behave as non-linear impedances shunting the line at regular intervals, the standing wave ratio would probably be poor and the reflections complex. Nevertheless, it should be noted that the diode spacing of $\frac{1}{4}\lambda$ is a maximum figure only and, as in the register just described, any number of additional stages could be inserted between these without affecting the basic functioning of the register or line. Hence one may again visualize a system in which the number of discrete tunnel diode elements is infinite and we return to a structure such as Fig. 5(c). If it became practical to manufacture such a strip of semi-conductor material by a continuous process, various applications might

be found as a substitute for conventional transmission lines.

5. Gates

The tunnel diode pair may be used as a multi-input gate in the circuit shown in Fig. 6(a). The gate would be energized by applying a clock pulse to the supply terminal V_s and the output condition would be determined by the sum of the currents flowing in the various input resistors. A compact form of construction for such a gate is self-explanatory in Fig. 6(b).

A rather more complex structure has been devised for a gate and store for a magnetic p.c.m. coder which is currently under development. In this coder the generated code appears as a parallel output on several digit windings; at each sampling instant the code appropriate to that sample is represented by positive (mark) pulses or negative (space) pulses at the terminals of the respective windings. Between samples the coder is made to change its condition in readiness for the next sample, and this change of condition is accompanied by the appearance of spurious outputs at the digit terminals.
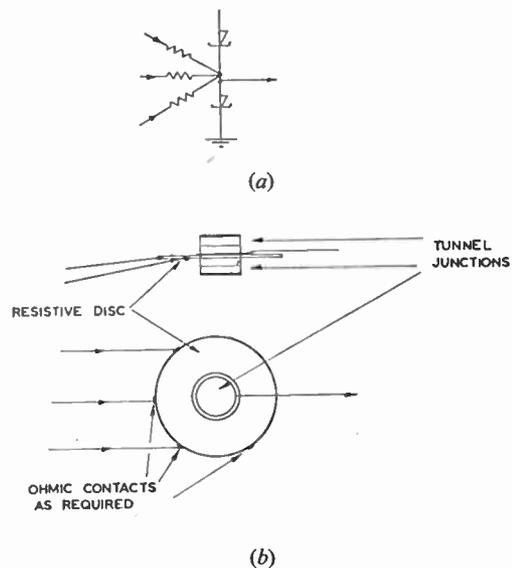
Fig. 6. (a) Elementary twin-diode gate.
(b) Possible form of construction.

The object of the gating and storage circuits is firstly, to eliminate these spurious outputs, and secondly, to store the parallel code prior to serializing for transmission. Power consumption, speed of operation and other limitations imposed by core characteristics have dictated a form of coder having a very small useful output, although otherwise successful. This small output (50 mV) could not be handled by conventional diode gates. Furthermore,
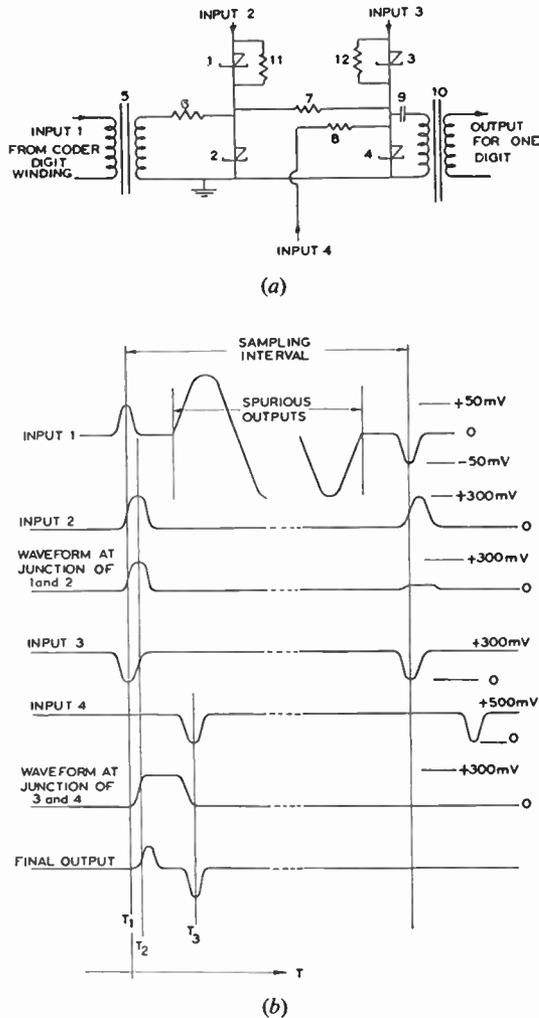
Fig. 7. (a) Gate and serializer for a magnetic p.c.m. coder.
(b) Waveforms for gate and serializer for magnetic p.c.m. coder.

the unpredictable d.c. component made it unreasonable to attempt linear amplification before gating. Hence progress with the magnetic coder was halted until the advent of the tunnel diode.

In Fig. 7(a) the gate comprises a tunnel diode pair D1 and D2, while a further pair D3 and D4 serve as the store. A circuit as shown is provided for each of the seven digit output windings. Consider the first digit only. The digit winding is connected via a suitable impedance matching transformer TR1 and a current limiting resistor R1 to the junction of D1 and D2. Between samples, when spurious outputs are appearing, the gating waveform—input 2—is at zero voltage. Hence the tunnel diodes D1 and D2 are operating on a low impedance part of their characteristic and short-circuit the coder output. The coder behaves as a relatively high impedance source when

generating spurious outputs, hence this "short-circuiting" gate is very effective.

At time t_1, the centre of the sampling period, the digit pulse—input 1—will have a magnitude of approximately 50 mV and polarity appropriate to the code element to be generated. At this instant the gating pulse—input 2—will be rising towards a maximum. When input 2 is at its maximum of say 300 mV either diode D1 or D2 may adopt a high impedance condition, but not both; the choice is determined by the polarity of the digit pulse as the gating pulse rises. This gives a very high sensitivity at the required instant. Hence for "mark" the junction of D1 and D2 will rise to a potential of almost 300 mV, while for "space" it will barely rise to 20 mV.

The storage so achieved will persist for so long as input 2 remains on, but is liable to be interfered with by subsequent spurious coder outputs, which may rise to as much as 2 V. Hence it is immediately transferred to a second store comprising diodes D3 and D4.

Here the energizing voltage—input 3—persists throughout, except during the sampling period. The interruption of input 3 is so timed as to produce a positive-going edge enabling the sampled information appearing at the junction of D1 and D2 to be transferred via the resistor R2 and stored at the junction of D3 and D4. The mechanism of storage is as before, but when input 2 ceases and the gate returns to its short-circuit condition spurious outputs are unable to affect the store.

In the absence of serial read-out pulses—input 4—the condition stored at the junction of D3 and D4 would remain until the next sample, that is until the next interruption of input 3. However, at a suitable time t_3 before the next sampling instant the read-out pulse is applied so as to return the junction of D3 and D4 toward zero potential. Supposing now that a "mark" had been stored; diode D3 would exhibit a low impedance and diode D4 would exhibit a high impedance. The junction would stand at +300 mV. When the read-out pulse is applied the junction will return to zero, the negative excursion being read as a "mark" output. If a "space" had been stored the junction would already lie close to zero, hence no output pulse would be generated.

The remaining digits would be dealt with similarly by their respective circuits, except that their read-out pulses would appear at successive times t_4, t_5, t_6, etc., the full serial code being completed before the next sampling instant. The output would be commoned by connecting in series all the output windings of the transformer TR2, a single series conventional diode being used to eliminate unwanted positive-going pulses. Resistors R4 and R5 might be included to balance the tunnel diode characteristics if required.
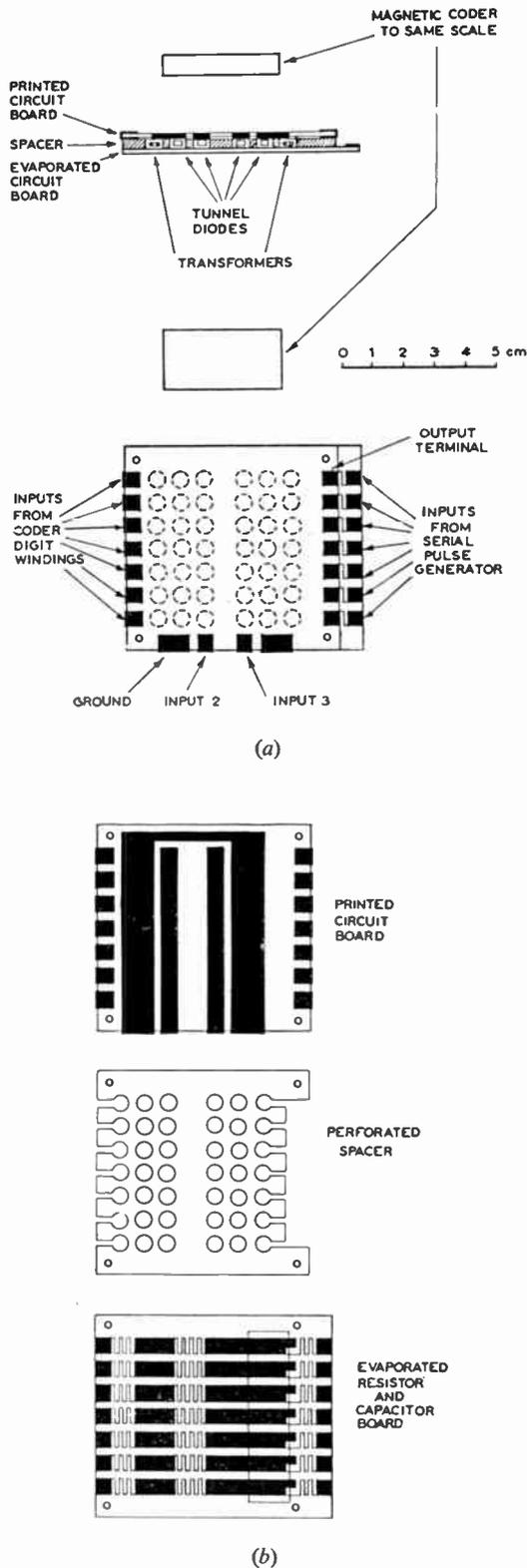
Fig. 8. The complete gate assembly.
(a) Plan and section.
(b) The separate components.

In a practical assembly the magnetic coder proper can be accommodated comfortably in a volume of $1\frac{1}{2}$ in. × $\frac{3}{4}$ in. × $\frac{1}{4}$ in. (4 cm × 2 cm × $\frac{1}{2}$ cm). The gate and serializer, if built with conventional components and tunnel diodes in standard cases, would be quite disproportionate in size. More significantly, since a single pulse generator is required to feed all the seven input 2 terminals in parallel, lead inductances make it difficult to supply identical gating waveforms to the stages. A similar argument applies to input 3. As a "solid state" circuit it would be feasible to construct the fourteen lower diodes on a single germanium wafer. The method does not commend itself, however, since the fourteen upper diodes must be separate. Instead, a sandwich-type structure has been devised, based on a very compact tunnel diode capsule. This capsule has the form of a flat disc $\frac{3}{16}$ in. in diameter and $\frac{1}{16}$ in. in thickness (5 mm dia. and $1\frac{1}{2}$ mm in thickness), the enclosure being a small ceramic ring capped by metal discs which serve also as the external contacts.

Figure 8(a) shows a plan and section of the complete gate assembly, Fig. 8(b) the separate components. All external connections are confined to the upper board, which might be constructed by conventional printed circuit methods. The lower board carries the seven groups of resistors R1, R2 and R3 together with the seven capacitors C1. All are made by vacuum evaporation through suitable masks. Since the resistance values are only a few hundred ohms, with very low power dissipation, only small areas of resistive film are required. Again, due to the very low working voltage of the tunnel diode, capacitors with evaporated film dielectrics may reach the required value in a much smaller space than would be required by a conventional component, which would of necessity have a much higher voltage rating than is called for here. In this form of construction the size of the complete gate and serializer is closely comparable with that of the magnetic coder proper.

In the present circuit it is appropriate to use small ferrite cores for the coupling transformers; these are mounted in suitable cavities formed by perforating the sandwich boards. For an assembly incorporating thin magnetic films it will be evident that these could be built into the lowest board as part of the vacuum evaporation process.

6. Conclusion

There is little doubt that the pressure for further miniaturization of digital circuits will continue since, quite apart from the desirable saving in space, the ever-increasing speed of operation will not tolerate the time delay involved in transmitting information across a large structure. It may well be that complex solid-state circuits will have their place here, but only

RESISTIVE JUNCTIONS
OR BACKWARD RECTIFIERS

UPPER CONTACT PLATE

CERAMIC

GE WAFER   TJ

TJ
GE WAFER

OUTPUT
TERMINAL

TRIGGER
TERMINALS

LOWER
CONTACT
PLATE

TJ - TUNNEL JUNCTIONS

0   1   2   3   4   5   mm
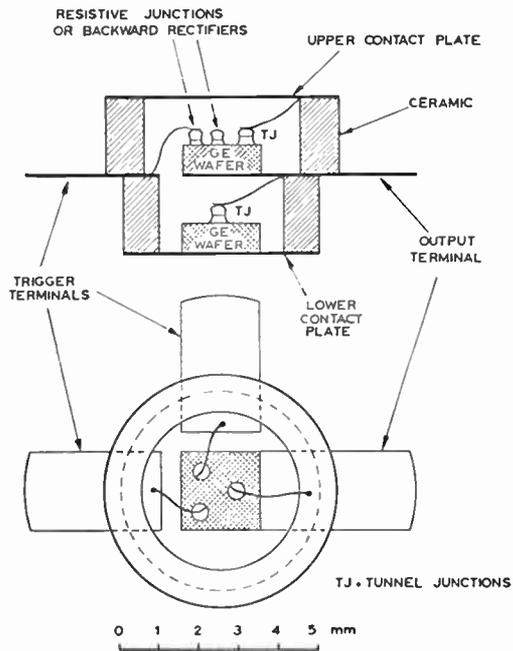
Fig. 9. Proposal for tunnel diode functional unit.

by a high level of mass production could such equipment be made sufficiently cheap and freely available. Taking any system functional block diagram, the optimum production technique would be to use solid-state circuit methods for building the individual blocks—pulse generators, gates, registers and stores. These individual blocks would be standard items ready for incorporation in a separately-made network of interconnections appropriate to the intended system function. The mass production of such a network is well anticipated by the proved techniques for producing multiple copies of a master pattern; printing, photography and vacuum evaporation through a mask. However, in the mass production of the individual circuit blocks it would be wrong to use solid-state methods merely to construct conventional circuits. To build, in the solid state, a complete two-transistor flip-flop containing more than a dozen components may be a considerable technical achievement but may never be an economic proposition for large-scale production. An almost equivalent two-state device need contain only two tunnel junctions and one resistor, with the added advantages of ruggedness, high speed and low power consumption to commend it.

Certainly the tunnel diode is not yet the ideal active device; there would, for example, be immediate application for a three-terminal device of the same

family, giving a sensitive trigger without internal feedback. The matched tunnel diode pair with a trigger input resistor is the nearest approach to such a device so far and might very well be used as a basic circuit block. A useful elaboration would be to provide more than one trigger terminal, as in Fig. 9, and perhaps to substitute the input resistors by backward rectifiers formed on the upper semi-conductor wafer. Assembling such devices as single encapsulated units should enable accurate matching of the peak currents of the tunnel junctions during production, with consequent high trigger sensitivity.

Although these twin-diode units would be versatile in their application as gates and stores, it must be remembered that the high trigger sensitivity does not represent a true power gain but relies on the method of control by master clock pulses. Hence to complete the picture there remains the need for a solid-state pulse generator, again capable of mass production in a simple capsule adapted for insertion into a prepared system network. Such a device should be capable of producing pulses of, say, 300 to 500 mV at a current of one ampere or more, and should have a sensitive trigger terminal. This is not necessarily a repetition of the desire for a tunnel triode having power gain, since linear amplification is not essential. The answer might be a rugged low-impedance equivalent of a *pnpn* switch, or possibly a device similar to a secondary voltaic cell which could charge continuously from the main power supply but would discharge completely through a fourth terminal whenever a trigger pulse were applied.

The best solutions to these problems will only come by the closest possible co-operation between the solid-state physicist and the systems and circuit engineer; the aim should not be to construct complex circuits in the solid state but rather to search for solid-state phenomena which make complex circuits unnecessary.

Whatever the nature of the solid-state unit, it will be of the utmost importance to ensure that the size of the enclosing capsule be sensibly related to that of the device it contains. This should not be so difficult to achieve in a device for which careful hermetic sealing is not required. The arrangement of external connections should be such that the capsule would fall naturally into its correct position in the external circuit, as in Fig. 9; this would materially assist the automatic assembly of a complete system.

The Design and Construction of Tunnel Diodes

By

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Presented at a joint meeting with the Institute of Physics on "Tunnel Diodes" held in London on 7th February 1961.

Summary: The electrical characteristics and principle of operation of two types of tunnel device are described: the tunnel diode and the uni-tunnel or backward diode. The considerations governing choice of base and alloying materials are discussed. Details are given of the processes used to manufacture germanium and gallium arsenide devices, particular attention being given to the method of achieving close tolerance of the peak current of tunnel diodes by a monitored etching technique. Results are presented which show the influence of processing parameters on device characteristics. The equivalent circuits of the devices are related to the basic properties of the elements and their encapsulation.

1. Introduction

The tunnel diode, also known after its inventor[1] as the Esaki diode, is the most recent arrival in the field of electronic devices. It falls into the class of voltage-controlled negative-resistance solid-state devices. Because of the principle by which it operates, the response of the device is very fast, and it is useful for a range of low-power applications including switching, memory, oscillation and amplification in the frequency range from d.c. to kilomegacycles.[2, 3, 4] However, the fact that the tunnel diode is a two-terminal device, and therefore completely bilateral, means that a new approach to the circuitry is needed.

In this paper we shall describe the design and manufacture of the tunnel diode, showing the influence of processing parameters on device characteristics. We shall also outline the design and construction of the backward diode and summarize the basic proposed applications.

2. Electrical Characteristic

2.1. *Description of Characteristic*

A tunnel diode consists of an abrupt junction formed between two semi-conductor regions having very high impurity concentrations. The total thickness of the transition region is of the order of 100 Å. A typical d.c. characteristic of such a diode, made in germanium, is shown in Fig. 1. It is compared with a conventional germanium junction diode (dotted curve). The tunnel diode has a low resistance region at low reverse and forward voltages, and a negative resistance region at higher forward voltages. At still higher forward voltages, the current increases again, and the characteristic becomes similar to that of an ordinary *p–n* junction.

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The reverse characteristic is due entirely to quantum mechanical tunnelling.[5] The forward current is the resultant of three distinct components:

(*a*) quantum mechanical tunnel current;

(*b*) minority carrier diffusion current;

(*c*) excess current, of unknown origin.

The characteristic of Fig. 1 is fairly typical of a germanium tunnel diode. The voltage at peak current is approximately 50 mV and at the valley current has a value in the range 250–400 mV. Voltage swings,
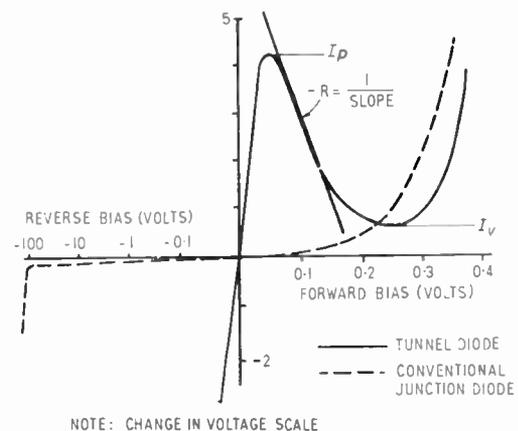
Fig. 1. Static characteristics of tunnel diode and conventional diode.

i.e. the difference between the voltage at the peak current and the voltage at the corresponding current on the minority carrier diffusion part of the characteristic are in the range 0·3–0·45 V. The corresponding parameters of a gallium arsenide tunnel diode are 100 mV, 450–650 mV and 0·8–1·2 V. Static characteristics of the two diodes are compared in

Fig. 2. The above voltages vary little from one device to another for any given material. The current scale, however, can be varied over a wide range by changing (1) the junction area, (2) the thickness of the transition region either by changing the initial doping level, or to a lesser extent, by modifications in the fabrication process. The present practice is to specify the diode
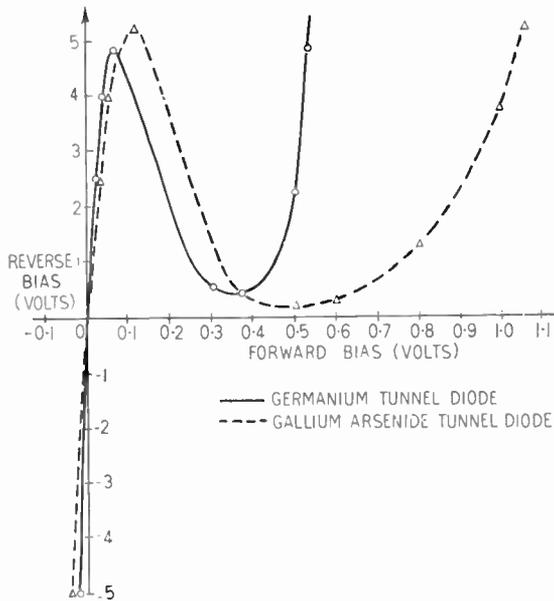
Fig. 2. Static characteristics of germanium and gallium arsenide tunnel diodes.

in terms of I_p and the ratio I_p/I_v; devices have been fabricated with I_p in the range 50 μA to 10 A and with current ratios (which should preferably be as high as possible) of 15 and 35 for germanium and gallium arsenide tunnel diodes respectively, at room temperature.

2.2. Principle of Operation

Because of the very high impurity concentration in the material from which tunnel diodes are constructed discrete acceptor and donor levels widen to become impurity bands which merge with the valence and the conduction bands. This has the effect of narrowing the width of the forbidden energy gap (e.g. the forbidden energy gap of Ge containing 10^{19} impurity atoms/cm^3 is equal to 0·67 eV)[6] and of increasing the densities of states in the bands. Also the Fermi levels penetrate into the conduction and the valence bands in the case of n-type and p-type materials respectively. The energy band configuration of the tunnel diode at zero bias voltage is shown in Fig. 3. In Fig. 3(a) the energy of a carrier is plotted as a function of its position in the crystal. E_c, E_v, are the conduction and valence band edges respectively, and

E_f is the Fermi level. ΔE is the forbidden energy gap. S_c and S_v are the penetrations of the Fermi level into the conduction and valence bands and S is the total penetration. The parameter S is of great importance for, as will be shown later, most of the tunnel diode properties can be expressed in terms of it. V_d is the diffusion voltage and, as can be seen from the diagram, it is equal to $(\Delta E + S)/q$. Because of the high value of S, V_d is much larger in the tunnel diode than in a conventional diode; this results in a very high built-in field ($\sim 5 \times 10^5$ volt/cm).

In Fig. 3(b) the densities of filled (shaded) and empty states are shown for the electrons in the conduction and valence bands at room temperature. The densities of states are assumed to be parabolic.

Only a short qualitative description of the carrier flow across the junction at different applied voltages will be given with the aid of the simple band picture of Fig. 4, as many detailed accounts of the above process (taking into consideration the densities of filled and empty states) exist already.[7, 8]

If we apply an external voltage so as to make the n-side more positive with respect to the p-side, i.e. apply a "reverse" bias, the p-side of the energy-level diagram will be shifted vertically relative to the n-side (Fig. 4(a)). The electrons in occupied states in the
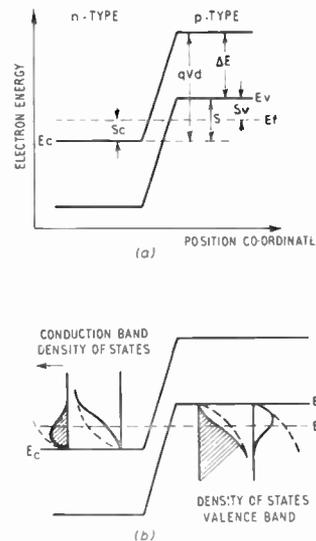
Fig. 3. Energy band diagram of tunnel diode.

valence band on the right can "see" unoccupied states of equal energy in the conduction band on the other side of the forbidden band. Normally, the forbidden band effectively isolates the electrons on the two sides of the junction, because it presents a potential barrier that the electrons cannot surmount, since they do not have sufficient energy. If, however, the
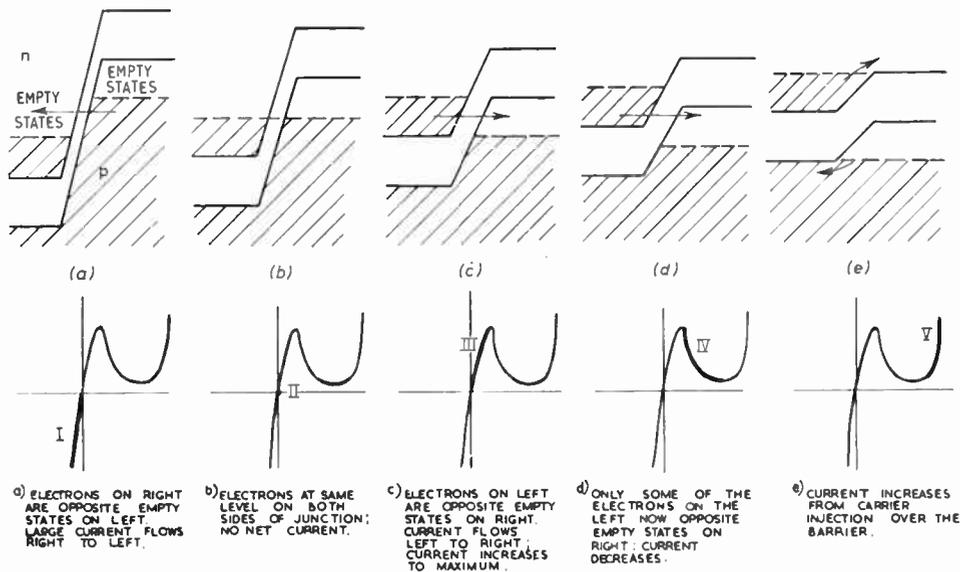
Fig. 4. Tunnel diode characteristics in terms of simple band picture.

junction region is thin enough, it follows from quantum mechanics that there is a finite probability that electrons originally on one side of the junction can appear on the other at the same energy. It is from this phenomenon of "quantum mechanical tunnelling" that the device derives the name of tunnel diode.

If the reverse bias of Fig. 4(a) is increased, the supply of electrons which are able to tunnel increases without limit, and gives region I of the characteristic. Region II, Fig. 4(b) corresponds to zero bias, and none of the electrons can see empty states to which they can tunnel. Of course, at any temperature above absolute zero, there are a few electrons with excess thermal energies which are able to tunnel to the other side of the junction. There is an equal probability of the same thing happening in the other direction, however, and no net current flows.

If a small forward bias is applied (Fig. 4(c)), some of the electrons at the bottom of the conduction band are now opposite empty states at the top of the valence band on the p-side of the junction and a forward current flows which increases with bias (region III). Eventually, this increase in bias begins to bring the forbidden region of the p-side opposite the conduction electrons on the n-side (Fig. 4(d)), fewer and fewer electrons are able to see empty states to which they can tunnel, and the forward current begins to decrease again (region IV). With still larger values of forward bias, the current remains small until appreciable minority carrier injection takes place (Fig. 4(e)), giving rise to the normal exponential forward characteristic of a p–n junction diode (region V).

3. Design Considerations

3.1. Forward Characteristic due to Tunnelling

The equation for tunnel current is usually written[1, 8] as the difference between the current from the conduction to the valence band (the "Esaki" current) and the current from the valence to the conduction band (the familiar Zener current):

$$I = AZ \int_{Ec}^{Ev} \rho_c(E)\rho_v(E)(f_c(E) - f_v(E))\, dE \quad \ldots\ldots(1)$$

where ρ_c, ρ_v, are densities of states in conduction and valence bands respectively; $f_c(E)$, $f_v(E)$ are Fermi functions (denoting the probability that a state at energy E is occupied). Z is the probability for a carrier to tunnel through the junction potential barrier. A is a constant involving junction area (and usually found by fitting eqn. (1) to experimental data). Assuming

$$\left.\begin{array}{c} \rho_c \propto (E - E_c)^{\frac{1}{2}} \\ \rho_v \propto (E_v - E)^{\frac{1}{2}} \end{array}\right\} \quad \ldots\ldots(2)$$

and considering small forward voltages V_F, it can be shown that the integral in eqn. (1) can be approximated by

$$\frac{qV}{4KT}(S - qV)^2, \quad \text{for } V_F \leqslant 100 \text{ mV} \quad \ldots\ldots(3)$$

where S is the total penetration of Fermi levels into the bands. It can be seen by differentiating eqn. (3) that the peak current occurs at a voltage given by

$$V_P = \frac{S}{3q} \quad \ldots\ldots(4)$$

Esaki[1] gives a value for S of 0.124 eV and a value for the peak voltage of 0.035 ± 0.005 V, which are reasonably consistent with formula (4).

Assuming that at the junction there exists a simple triangular barrier of height $\Delta E/q$, and taking the average particle energy as $E = \Delta E/2$, the following expression can be derived for Z, the tunnelling probability[9]:

$$Z = \exp - \left[\frac{2\sqrt{2\pi}}{3hq} \cdot m_r^{*\frac{1}{2}} \varepsilon^{\frac{1}{2}} n^{*-\frac{1}{2}} \Delta E^{\frac{1}{2}} (\Delta E - qV)^{\frac{1}{2}}\right] \quad ...(5)$$

where

$$m_r^* = m_v^* m_c^* / m_v^* + m_c^* = \text{reduced effective mass}$$

and

$$n^* = \frac{n_D n_A}{n_D + n_A} \qquad ......(6)$$

m_c^*, m_v^* are effective masses of carriers in the conduction and valence bands.

n_A, n_D are respectively the majority carrier densities,

h is Planck's constant,

q is the electronic charge,

ε is the dielectric constant,

ΔE is the width of the band gap,

V is the applied voltage.

It can be seen from eqns. (3) and (5) that to obtain large tunnel currents a semi-conductor with low carrier effective mass, small forbidden gap, and highly doped p-type and n-type regions should be used.

3.2. Negative Resistance

Gremmelmaier and Henkel[10] state that to a first approximation

$$|R| \propto \frac{1}{AZ} \qquad ......(7)$$

where $|R|$ is the modulus of the negative resistance, A is the junction area and Z the tunnelling probability.

3.3. Junction Capacitance

The total capacitance of a p–n junction consists of a parallel combination of two capacitances.

$$C = C_T + C_D \qquad ......(8)$$

where C_T = transition or space charge capacitance due to the fixed ionized impurities on both sides of the junction.

C_D = diffusion or storage capacitance associated with the minority carrier diffusion.

In a tunnel diode junction C_T predominates over C_D in the useful forward voltage range. The low value of C_D is due to the small value of minority diffusion current and the low minority carrier lifetime. The transition capacitance is given by

$$C_T = A \left[\frac{q\varepsilon}{2(V_d - V)} \frac{n_D n_A}{n_D + n_A}\right]^{\frac{1}{2}} \qquad ......(9)$$

where V_d is the diffusion voltage and V the applied voltage.

3.4. Series Resistance

The negative resistance of a tunnel diode is partially compensated by a series resistance R_S. This series resistance arises from the spreading resistance in the semi-conductor wafer and the resistance of the leads and contacts. To obtain low capacitance values the tunnel junction areas are deliberately made small by electrolytic etching. This means that the series resistance is mainly caused by the spreading resistance. Thus

$$R_{S1} = \frac{\rho t}{A} = \frac{t}{q\mu n_I A} \qquad ......(10)$$

where ρ is the resistivity, t the thickness, μ the carrier mobility and n_I the impurity concentration in the semi-conductor wafer. This applies for a cylindrical configuration.

It has been found that the shape of the etched wafer is not properly cylindrical, but can be approximated by a frustum of a cone. Thus

$$R_{S2} = \frac{4t}{\pi d_1 d_2 q\mu n_I} \qquad ......(11)$$

is a more accurate formula. d_1 and d_2 are the diameters of the etched semi-conductor material at the junction and at the ohmic contact respectively.

3.5. Frequency Response

The upper frequency limit of a tunnel diode is restricted mainly by the $|R|C$ product (the device time constant) (see eqn. (12)). It can be deduced from eqns. (7) and (9) that this product is independent of the junction area. Assuming that $n_A = n_D = n_I$ we obtain from eqn. (9)

$$C_T \propto \left(\frac{n_I}{2}\right)^{\frac{1}{2}}$$

and from eqn. (7)

$$|R| \propto \exp k \left(\frac{2}{n_I}\right)^{\frac{1}{2}}$$

Thus, on increasing the doping level on both sides of the junction, decrease of $|R|$ is more rapid than the increase of C_T, therefore the RC product is decreased resulting in a higher frequency cut-off.

Sommers[2] states that $|R|C$ (for germanium tunnel diodes) decreases from 5×10^{-9} to 5×10^{-11} second as the doping concentration of the starting material increases from 2.4 to 4.8×10^{19}/cm³.

Z, the tunnelling probability, depends also (eqn. (5))

on the effective masses of carriers, the energy gap and the dielectric constant of the semi-conductor used for fabricating tunnel diodes. In the case of GaAs the energy gap is large in comparison with Ge. The effective mass, and the dielectric constant, however, are smaller, and, therefore, for a given doping level, GaAs devices have better frequency performance. The lower dielectric constant results also in a lower capacitance for GaAs.
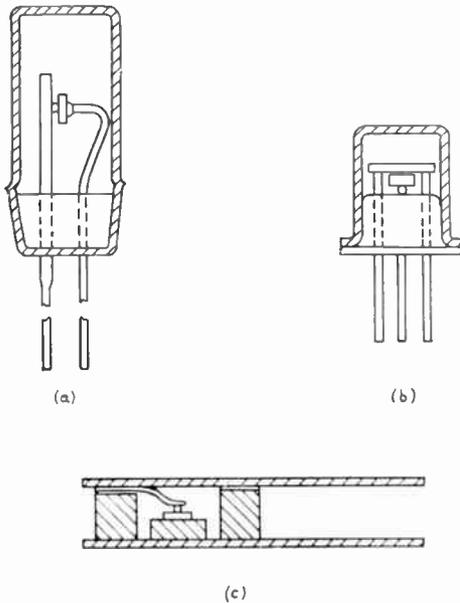
Fig. 5. Various tunnel diode encapsulations.

The cut-off frequency is also a function of the series resistance R_S, which should be as small as possible. This is achieved by using a very thin and heavily doped semi-conductor wafer. For a given doping level the n-type material has a lower resistivity; hence it would seem to be advantageous to use n-type semi-conductor wafers.

There are other design considerations besides the frequency response. For example, the voltage swing which is a function of the energy gap should be, for most applications, as large as possible since this is the voltage available for subsequent stages. Another important parameter is the maximum operating temperature. Tunnel diodes can operate from liquid helium temperature to temperatures above those of transistors made from the same semi-conductors. The maximum operating temperature is a function of the forbidden energy gap. Thus, InSb diodes have to be cooled to at least $0°$ C, preferably to $77°$ K;[11] practical upper limits for germanium and silicon tunnel diodes have been quoted as $200°$ C and $350°$ C respectively[2] and GaAs tunnel diodes have operated at $300°$ C.[12]

4. Fabrication Process

4.1. *Germanium Tunnel Diode*

Heavily doped germanium crystals of (111) orientation are grown, using gallium as doping impurity, the carrier concentration varying between 1 and 7×10^{19} carriers/cm³ as determined by measuring the Hall coefficient. The crystal is sliced and approximately 0·005 in. thick wafers are alloyed with 0·006 in. diameter Au(73·1%)/Sb(24·4%)/As(2·5%) spheres in a hydrogen atmosphere. Ohmic contacts are obtained by alloying at the same operation either indium spheres or clad Kovar discs, depending on the final encapsulation desired. The tunnel diode element is mounted on one of the seals shown in Fig. 5.

As shown in Section 3.1 the peak current density of a tunnel diode is governed by the impurity concentrations on both sides of the junction. Thus, the current density can be varied, either by varying the impurity content of the starting material (see Fig. 6), or by changing the doping level in the re-grown region. This can be done by varying the alloying temperature, or by using impurities with higher segregation coefficients (see Fig. 7). In Fig. 6 the variation of the peak current with the doping level in the starting
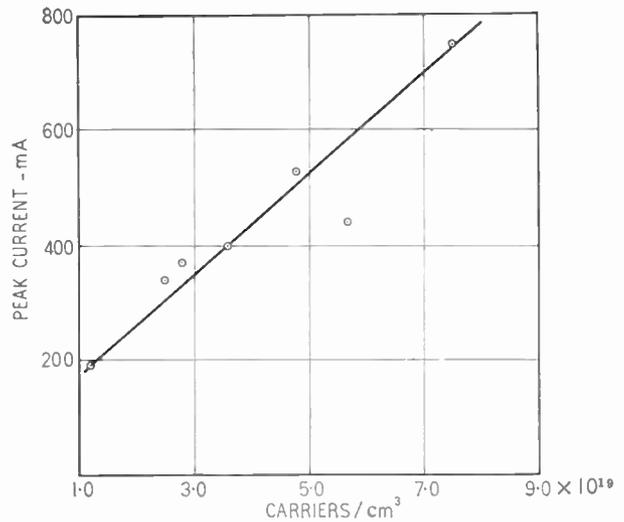
Fig. 6. Peak current vs. impurity concentration.
For devices made with 0·0135 in. dia. Au (75%) Sb (25%) spheres.

material is not as large as that found by other workers.[13] This is caused by the use of antimony to regrow the n-type region. Since the segregation coefficient of antimony is rather low, n_D is small in comparison with n_A; therefore n^* (see eqn. (6)) does not increase very rapidly with the increase of n_A.

The variation of current density with the alloying temperature for devices made with Au/Sb/As spheres
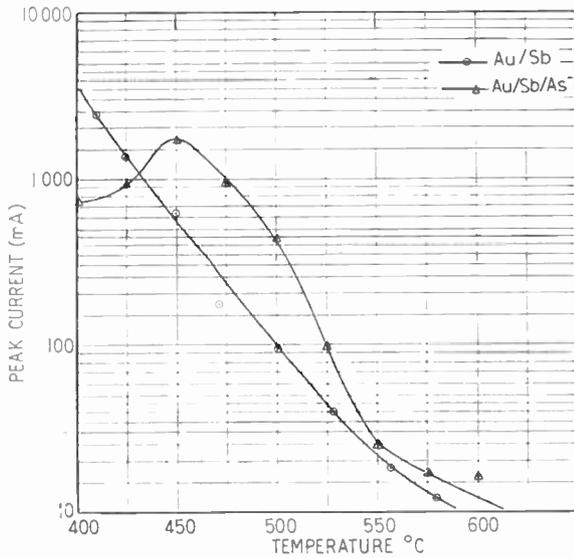
Fig. 7. Peak current vs. alloying temperature.

For devices made with 0·006 in. dia. Au/Sb/As spheres and 0·0135 in. dia. Au/Sb spheres. Hole concentration in Ge 4×10^{19} cm^{-3}.

is shown in Fig. 8. The corresponding variation of the ratio of the currents with the alloying temperature is shown in Fig. 9. In the above experiments the carrier concentration in the starting material is 4×10^{19} cm^{-3}.

It is very difficult to estimate the doping level in the re-grown region, as the ternary segregation coefficients for Sb and As are not known; the variation of the segregation coefficients with temperature is also uncertain.
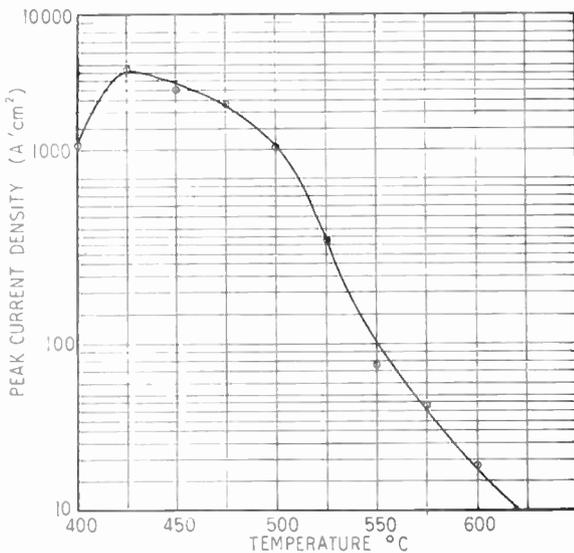
Fig. 8. Peak current density vs. alloying temperature.

For devices made with 0·006 in. dia. Au/Sb/As spheres. Hole concentration in Ge 4 × 10^{19} cm^{-3}.

To obtain low capacitance values, and to control the peak currents to close tolerances, devices are etched electrolytically in a 28% potassium hydroxide (KOH) solution. The etching rate depends mainly on the etching current density. To achieve close tolerance of the peak current the device is etched for 3 seconds, and its characteristic displayed on a curve tracer for 1 second. Since the immersion of the device in the electrolyte introduces effectively a low resistance in parallel with the junction, the value of the peak current appears to be increased. Therefore, during final etching the device is taken out of the etching solution and washed before its characteristic is displayed on the curve tracer. In this way peak currents can be controlled to within 2%.

It is evident that this principle can be extended to enable devices in production quantity to be etched automatically to precise values of peak currents.
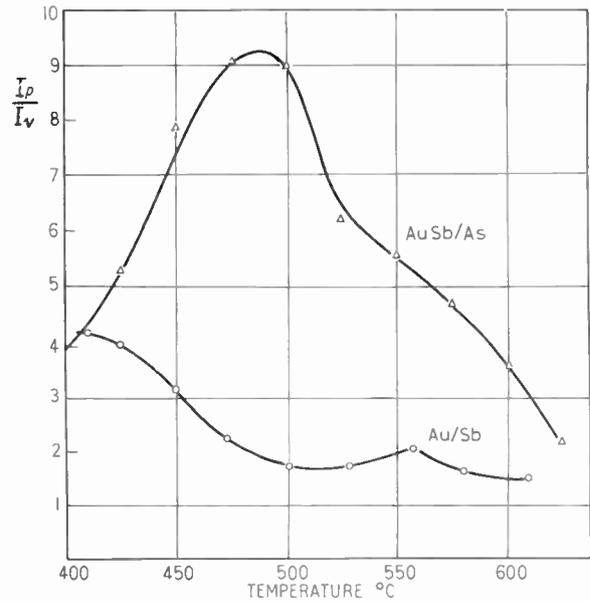
Fig. 9. Ratio of the currents vs. alloying temperature.

For devices made with 0·006 in. dia. Au/Sb/As spheres and 0·0135 in. dia. Au/Sb spheres. Gallium concentration 4 × 10^{19} atoms cm^{-3}.

4.2. Gallium Arsenide Tunnel Diode

Gallium arsenide tunnel diodes have been fabricated from polycrystalline starting material, the necessary high impurity concentration being obtained by zinc diffusion. Thin, etched, gallium arsenide slices are placed in a 15 cm^3 silica ampoule with zinc ranging in quantity from 5 mg to 50 mg. The ampoule is so designed that the zinc and gallium arsenide slices can be kept at two different temperatures in order to control the doping level. To prevent decomposition of the gallium arsenide slices, a quantity of free arsenic is enclosed in each ampoule to establish a high vapour

pressure. The ampoules are initially evacuated and, after sealing, they are fired at a high temperature. Gallium arsenide wafer temperatures are in the range from 950° C to 1050° C, and those of the zinc from 800° C to 925° C. The slices are cut into wafers which are alloyed with tin or tin (95%)/germanium (5%) in a hydrogen atmosphere. Ohmic contacts are obtained by alloying the GaAs wafers to gold-clad Kovar discs.

5. Equivalent Circuit

The electrical characteristics of the tunnel diode can be represented by an equivalent circuit shown in Fig. 10. Here $-R$ is the negative resistance which arises, as previously explained, from quantum mechanical tunnelling of electrons through the junction. The negative resistance is virtually independent of frequency from d.c. to the microwave region; it also shows little dependence on temperature.[14] It is a function of the applied bias voltage, exhibiting a
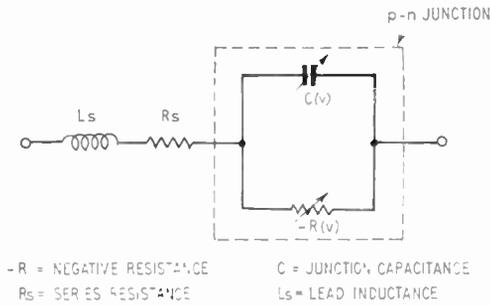
Fig. 10. Equivalent circuit of the tunnel diode.

minimum value and becoming infinite at the peak and valley currents. The minimum value can be varied from a fraction of an ohm to hundreds of ohms by changing either the junction size or the doping level on one or both sides of the junction.

In parallel with the negative resistance there exists a junction capacitance which is, as shown in Section 3.3 mainly due to the fixed ionized impurities on both sides of the junction. This capacitance is, therefore, quite large in comparison with the capacitance of a conventional diode. Typical capacitance values range from 1–5 μF/cm^2 of junction area, depending on the doping level.

The resistive cut-off frequency is defined by

$$f_{max} = \frac{1}{2\pi|R|C}\sqrt{\frac{|R|}{R_S} - 1} \qquad \ldots\ldots(12)$$

and the self-resonant frequency by

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{L_S C} - \frac{1}{C^2 R^2}} \qquad \ldots\ldots(13)$$

In eqn. (12) R_S is the series resistance, which consists mainly of the spreading resistance in the etched germanium or gallium arsenide wafer, and also includes the lead resistance. In a germanium tunnel diode, of 10 pF capacitance, $R_S \simeq 1\ \Omega$. In gallium arsenide devices R_S ranges from 2 to 5 Ω.

In eqn. (13) L_S is the series inductance, and it is predominantly a function of the encapsulation. The inductance values for the different types of encapsulation shown in Fig. 5 are as follows:

(a) $L_S = 8$ mμH

(b) $L_S = 4\cdot5$ mμH

(c) $L_S < 1$ mμH

Thus for very high frequency work (above 1 kMc/s) an encapsulation similar to type (c) is essential.

6. Backward Diode

On inspecting the reverse part of a tunnel diode characteristic we see that the breakdown occurs at zero voltage, giving rise to large currents at very low voltages. If the forward current of the diode is made very small, such a device acts as a low voltage rectifier, the forward current being now equivalent to the leakage current of a conventional diode. The reverse current in the tunnel diode is, as has been explained already, due to internal field emission (tunnelling) making the charge storage effect very small.

A device of this type is therefore capable of high frequency operation. For circuit applications the reverse characteristic is used as the forward or low impedance direction, and therefore this device is called a "backward diode".
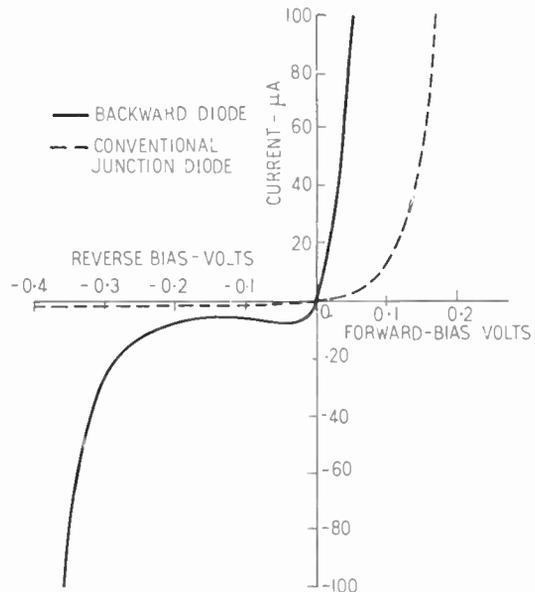
Fig. 11(a). Static characteristics of backward diode and conventional diode.

A typical characteristic of a backward diode is shown in Fig. 11. It is compared with a conventional diode (dotted curve). For comparison purposes the polarity of the backward diode shown in Fig. 11 has been reversed, i.e. the current shown for forward voltages has been obtained by applying the positive bias to the *n*-type region of the backward diode. Figures 11 (*a*), (*b*) and (*c*) show the backward diode and conventional diode characteristics to different scales. For a typical device, current at $+200$ mV (i.e. in the high impedance direction) is less than 10 µA, and at -200 mV it is approximately 10 mA, thus giving a rectification ratio greater than 1000. The junction capacitance at $+200$ mV is equal to 40 pF. The variation of the junction capacitance with the applied bias voltage is shown in Fig. 12.

Fig. 11(*c*). Static characteristics of backward diode and conventional diode.

Fig. 11(*b*). Static characteristics of backward diode and conventional diode.

Germanium backward diodes have been fabricated from *n*-type starting material with a doping level of 1×10^{19} carriers/cm^3 obtained by antimony diffusion. Germanium slices 0·006 in. thick and with faces coincident with a (111) plane are sealed in an evacuated silica ampoule with polycrystalline germanium shot containing 1·3% antimony. The silica ampoule is next fired at 850° C.

The slices are cut into wafers, and these are alloyed with 0·008 in. indium (99·6%)/gallium (0·4%) spheres. Ohmic contact is obtained by alloying the germanium wafer with a clad Kovar disc. Devices are etched electrolytically until the currents at $+200$ mV are smaller than 10 µA.

Backward diodes can be used in conjunction with

tunnel diodes in computer circuits. Figure 13 shows two divide-by-two circuits. It can be seen that in these circuits backward diodes are used as gates.

In Fig. 13(*a*) voltage change due to the switching action of the tunnel diode at points A and B is of the order of 150 mV. This change of voltage must appreciably affect the resistance of the gates. The above change of voltage is not substantial enough for a conventional diode, but does produce the desired effect with the backward diode. Similar considerations apply in Fig. 13(*b*).
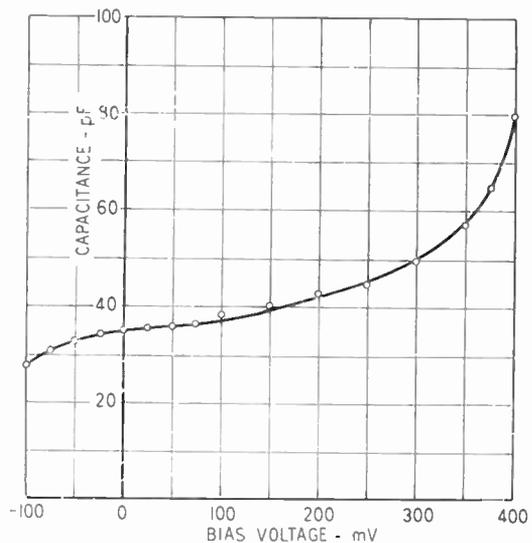
Fig. 12. Junction capacitance vs. bias voltage.

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BACKWARD DIODE

TUNNEL DIODE

(a)

(b)
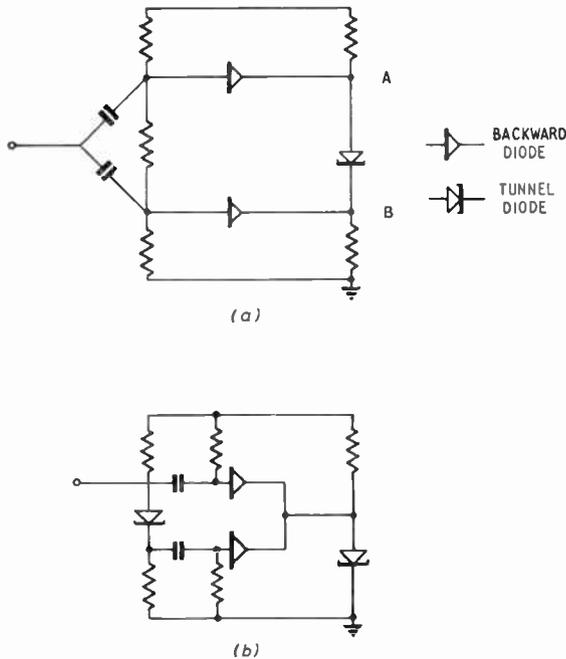
Fig. 13. Divide-by-two circuit.

For a detailed explanation of the operation of these circuits reference can be made to the paper "Tunnel devices as switching elements" by R. W. A. Scarr and I. Aleksander, presented at this symposium.†

Backward diodes can be used for meter protection and for low-level rectification. Voltages of peak values of 50 mV can be detected with a higher degree of efficiency than in the case of a normal diode. In a particular radio receiver circuit a backward diode had operated at a r.f. level which has been 13 dB lower than that of a normal diode of the same detection efficiency.

7. Acknowledgment

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† *J.Brit.I.R.E.*, **23**, 1962 (to be published).

News from the Sections . . .

Southern Section

On 12th October at Southampton University, Mr. J. E. V. Tyzack, C.B.E., introduced an informal discussion on "The Position of the Engineer in Management". He began provocatively by stating that the engineer had no special claim to a managerial position and might well be unsuited for that function. The most important concern of a manager was people and not things.

Management was defined as the bringing together of a number of activities and co-ordinating them so that they could be brought to bear effectively on the achievement of a predetermined aim. A manager could not be defined, but his job would involve creative ability, a planning function concerned with finance, provisioning, production, organization, direction and control. The qualities required were competence in some skill, tolerance, intuitive response to situations, ability to deal with complex situations, and a well-developed curiosity. When selecting a manager, the points to look for in order of priority, were: 1. Toughness and resilience; 2. Ambition; 3. Desire for responsibility; 4. Capacity for persuasion; 5. Social competence; 6. Intelligence. Mr. Tyzack omitted leadership because he maintained that it was a quality which could not be determined until authority was exercised.

He continued: "Few men are born managers although most must learn to become one; it is something that cannot be taught. The engineer must broaden his outlook and fundamentally the art of management can only be learned from and with the co-operation of his superiors. An important function of a manager is to select and train his successor, but this duty is very often shirked."

Mr. Tyzack then touched on the present shortage of managers, the importance of engineers realizing that human beings could not be measured and controlled, the current fantastic rate of change in the industrial world and the need, above all else, for adaptability.

A lively discussion followed in which training for management was criticized and it was generally agreed that, while a person could be helped to develop, the selection of a trainee at an early age and formal training was not a good thing. The suitable man should be able to be recognized by the age of about 30. This led to the suggestion that another quality a manager should possess was the ability to recognize desirable qualities in others. In engineering, if absolute measurement was impossible then one resorted to comparison. Mr. Tyzack opposed this view because environment could radically alter a judgement made under certain conditions. He regarded engineering techniques as a handicap rather than a help in management.

The problems of personnel selection by means of interviews were discussed at length and the conclusion reached that a risk was taken. This risk could be minimized by deciding what qualities were required for the job, by leaning heavily on the man's past record and by taking plenty of time in making an assessment in order to make allowances for one's own prejudices. Another speaker suggested that the application of new ideas in industry was hampered by the lack of engineers in managerial positions who could appreciate the potentialities. The non-technical man tended to play safe. The newer electronic industries were now beginning to have a much higher proportion of scientifically trained men in executive positions and Mr. Tyzack pointed out that time would prove whether this was successful or not.

Another contributor stressed the need for a manager to desire responsibility and considered that the modern educational system did not produce young people with the right outlook in this respect. Professor Zepler thought that ambition and the desire for power could lead a manager to make unwise decisions if too obsessed with himself. Mr. Tyzack agreed that these qualities must be present in moderation and not carried to extremes. Ideally, the requirement was for a man whose abilities and ambitions were matched.

J.M.P.

South Midlands Section

At the second meeting of the session held on 2nd November, at Malvern, Mr. R. A. Lampitt (*Member*) read a paper on "Transistor Portable Receivers". Mr. Lampitt began by reviewing some of the characteristics of transistors and showed their application in amplifier design. He then considered a six transistor receiver in detail, explaining the additive mixing employed, i.f. amplifier design and design of the output stage. He pointed out the difficulties of applying a.g.c. and showed some practical solutions.

An interesting part of Mr. Lampitt's paper discussed the use of Class B conditions in the output stage for low quiescent current drain, and he pointed out that it was essential to minimize cross-over distortion as much as possible; this sounded like a loudspeaker rattle and could mislead service engineers. The temperature condition of the output transistors was obviously important and the use of thermistors and high stability resistors to offset temperature variations was discussed. Methods of applying negative feedback were also described. The practical difficulties of packing the receiver inside the case was a point Mr. Lampitt mentioned and he instanced as an example the proximity of the ferrite rod aerial to components which might in certain circumstances be radiating, e.g. a "ringing" output transformer.

G.W.M.

Simultaneous Study of Drifts at Different Levels in the Ionosphere by the Spaced Receiver Method

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AND

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Summary: Results of simultaneous study of drifts in F1 and F2 regions of the ionosphere measured at Waltair over a period of two years are presented. F2 drift speeds are generally found to be higher than F1 drift speeds measured simultaneously. On a few occasions when f_0F1 was high, F2 drift velocity measurements are affected by drifts prevailing in F1 region at that time. It was found that F2 drift measurements are affected by the Es region when F2 region operating frequency is sufficiently close to or even above fEs. F2 region drift gradients have also been estimated by simultaneous study on two frequencies and drift gradients less than 1 m/s per km are reported.

1. Introduction

A systematic study of drifts in the different regions in the ionosphere has been in progress at Waltair (17° 43′ N, 83° 18′ E; magnetic latitude 9° 30′) for the last few years. When discussing the results of drift measurements published in a recent communication,[1] the authors have pointed out the possibility of some of the F2 region drift measurements being affected by F1 region drifts prevailing at that instant. Since the drift velocities are arrived at by comparing the fading patterns at three receiving sites, they should correspond to the level at which the fading is superposed on the signal. Booker[2] has given a valid theoretical basis for the assumption that the fading is imposed on the wave near the level of reflection, where the wavelength in the medium is large. Jones[3] came to the same conclusion by studying the E region drifts at two levels simultaneously. Probably the best method of determining the effect of a lower region on the fading of radio waves reflected from a higher region is to determine the drifts at the two levels simultaneously, as it is very well known that drifts at all levels in the ionosphere show short time fluctuations in magnitude and direction. In this communication we present the results of simultaneous study of drifts in the F1 and F2 regions, and Es and F2 regions. This technique has also been utilized to determine simultaneously drifts at different levels in the F2 region with a view to estimating the height gradient of drift velocities. The method used for the study of drifts is the spaced receiver method of Mitra[4] modified as described in an earlier paper.[5] Another similar equipment has been used for taking simultaneous measurements of drifts on two different frequencies.

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2. Simultaneous Study of Drifts in the F1 and F2 Regions

For this investigation observations were taken at 0900, 1200 and 1500 hours I.S.T. on frequencies 4·2–4·8 Mc/s for the F1 region and 6·0 Mc/s for the F2 region. The equivalent heights of reflection were in the range of 200 to 240 km for the F1 region and 280–320 km for the F2 region. To avoid the vitiating effect of the Es region when present, the records were taken only when fEs is less than the operating frequency by at least 1·0 Mc/s. Although about 140 pairs of useful records were obtained, seven records had to be rejected on account of the abnormally high velocities. Out of the remaining 133 pairs of records only 28 records gave F1 drift speeds even slightly greater than F2 drift speed obtained simultaneously. Figure 1 shows the histograms drawn for the 133 records giving the variation of number of observations versus the drift speed for both F1 and F2 regions. It will be seen from this histogram that the F1 drift speed lies in the range of 30 to 130 metres/second whereas the F2 region drift speed lies between 30 and 150 m/s. It can also be seen that the most frequent drift speed is about 75 m/s for the F1 region and 85 m/s for the F2 region. There is a larger number of F1 observations showing drift speed below 80 m/s whereas there is a larger number of F2 observations showing drift speeds above 80 m/s. These conclusions are in complete agreement with our results on F1 and F2 region drift measurements published earlier.[1] Thus it is evident that F2 region drift speeds are in general higher than the F1 region drift speeds measured simultaneously. By taking the average value of drift speeds at these three hours for the two regions the average gradients of drift speed between the F1 and F2 regions are estimated and are found to be approximately 0·9, 0·7 and 0·6 m/s for 1 km of virtual height change for the hours 0900,

1200 and 1500 respectively. There is thus some evidence of diurnal variation of the average gradient of drift speed between the F1 and F2 regions.

The data of simultaneous drift observations for the F1 and F2 regions have been examined to see if the F1 region influences drift measurements on the F2 region. Observations taken at 1200 hours I.S.T. gave drift directions which are generally the same for both the regions, being directed towards south-west. However, from the study of the diurnal variation of F2 region drifts carried out over a period of two years, it was established that the expected F2 region drift direction at this hour is nearly the same as that for the F1 region. In view of this coincidence of the
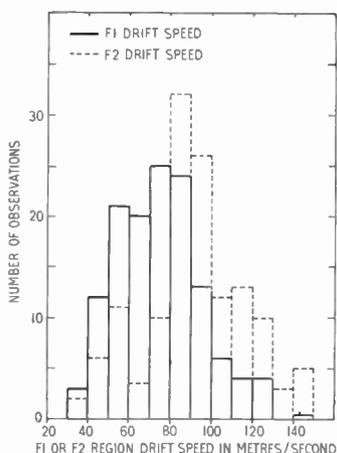
Fig. 1. Comparison of F1 and F2 drift speeds.

expected drift direction for both these regions, it has not been possible to examine the influence of F1 region drifts on F2 region drifts from observations taken at noon. But in the case of observations taken at 0900 hours for summer and at 1500 hours for spring and summer seasons, the drift directions for the F1 and F2 regions are expected[1] to be exactly opposite, being north-east for F1 and south-west for F2. Although the results of simultaneous observations for a majority of the records were in agreement with this conclusion, there are some records which gave the same drift direction, for both the regions, particularly on the days when f_0F1 is high. The authors suggest that on these few occasions the F2 drift measurements are sufficiently influenced by the F1 drifts prevailing at that time to yield nearly the same drift velocity. This problem of the effect of the lower region drifts on drift measurements for a higher level could be studied more extensively and exhaustively using Es and F2 regions, as it is possible to get widely varying ionization densities for the Es region.

3. Simultaneous Study of Drifts in Es and F2 Regions

Simultaneous study of drifts in the Es and F2 regions is undertaken mainly with a view to estimating quantitatively the conditions under which a lower absorbing layer affects the drift measurements taken on a higher reflecting layer. For this study observations were taken when both blanketing type and patchy type sporadic E were present. When patchy type Es was observed, simultaneous drift records on the Es and F2 regions were taken using a common transmitter radiating on a fixed frequency which is about 0·5 to 1·0 Mc/s below fEs such that reflected pulses of appreciable amplitude are obtained on both Es and F2 regions. When blanketing type of Es was present, two sets of simultaneous drift records were taken using two different transmitters radiating on different frequencies. The operating frequency for obtaining reflections from Es layer is adjusted to be about 0·5 to 1·0 Mc/s below fEs and is the same for both sets of records. The operating frequency for obtaining reflections from the F2 region is however adjusted to be different for both the sets. For one set the F2 operating frequency is adjusted to be slightly higher than fEs, the difference however being not more than 0·8 Mc/s. In the second set of records taken almost immediately after the first set, the F2 operating frequency is adjusted to be much higher than Es, the difference being generally greater than 1 Mc/s. Records were taken during day and night whenever Es is observed but a majority were taken during daytime. About 250 sets of records were taken during the two-year period of 1956–1958, but only 100 sets of records were found to be useful. The remaining records have to be rejected either due to lack of sufficient similarities in the spaced receiver records for Es or lack of fading for F2 records which is a common feature at frequencies above 7 Mc/s. Out of the 100 sets of useful records about 36 sets correspond to the patchy type of Es condition, when
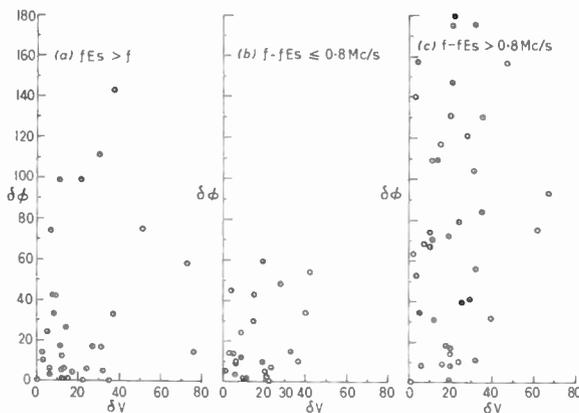
Fig. 2. Effect of Es region movements on F2 region drifts.

observations were taken on a frequency less than fEs. It is found that in almost all these records the drift direction obtained for F2 region reflections is different from the general drift direction expected for the F2 region at that time. However, it is interesting to note that the F2 region drift direction is the same as that observed for Es region. This close agreement in the drift directions for both these regions is very well illustrated in Fig. 2(*a*) which is a plot of $\delta\phi$ versus δV, $\delta\phi$ and δV being the differences in drift directions and drift speeds for the F2 and Es regions. This figure clearly illustrates the general agreement in the drift direction for a majority of the records, the differences being mostly in the range of 0–40 degrees. It may be concluded that F2 drift measurements taken when reflections from the patchy type of Es are observed on the same frequency lead to results which are considerably influenced by horizontal movements in the Es layer.

The remaining records taken on a frequency higher than fEs are divided into two groups; namely (a) when $f-f$Es $\leq$ 0·8 Mc/s, and (b) when $f-f$Es $>$ 0·8 Mc/s. Figures 2(*b*) and (*c*) show plots of $\delta\phi$ versus δV for these two cases, which clearly reveal the distinct difference between these two groups of records. In Fig. 2(*b*) the differences in drift direction $\delta\phi$ for a majority of the records do not exceed an angle of about 30 deg, indicating the predominant influence of the Es region on the F2 region drift measurements which normally gives different drift direction at that time; whereas in Fig. 2(*c*) it will be seen that the two drift directions observed for the two regions are generally different the values of the difference $\delta\phi$ being widely variable. It may be therefore inferred that drift measurements taken on the F2 region under these conditions are unaffected by the lower Es region provided the operating frequency is well above fEs the difference being not less than 0·8 Mc/s.

The effect of the lower absorbing layer on the fading of reflections from a higher layer is illustrated very vividly in the set of records reproduced in Fig. 3. Figures 3(*a*) and (*b*) illustrate spaced receiver drift records taken on the same frequency of 6·6 Mc/s on patchy type Es and F2 regions respectively. It will be clearly seen from these two records that the fading on the F2 region is clearly due to the Es region whose fEs is about 7·2 Mc/s because such a rapid fading is seldom observed on reflection from the F2 region. Figure 3(*c*) which is a record taken almost immediately on a frequency of 7·8 Mc/s shows the normal slow period fading generally observed on F2 region. The change in the type of fading observed on F2 region when the operating frequency is changed from 7·8 to 6·6 Mc/s is explained as due to the influence of Es layer in the later case as the operating frequency is less than fEs. It is therefore evident that

for these records the quick period fading observed on F2 region reflection is superposed at the Es region level and hence the drift measurements made on such records refer to conditions obtaining in the Es region.

4. Estimation of Height Gradient of Drift Speed in F2 Region

The technique of simultaneous study of drifts on two different frequencies is conveniently utilized for taking records on reflection from two different levels in the F2 region with a view to estimating the height gradient of drift speed which has not so far been estimated reliably. Records were taken on two frequencies such that the virtual height difference is about 100 km, the lowest value of virtual height being 250 km. Observations were confined to
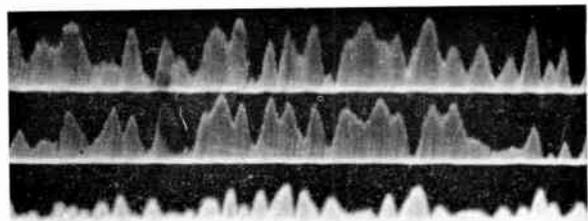
(*a*) Es region, 6·6 Mc/s.
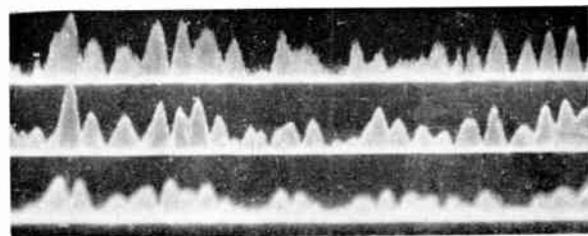
(*b*) F2 region, 6·6 Mc/s; fEs = 7·2 Mc/s.
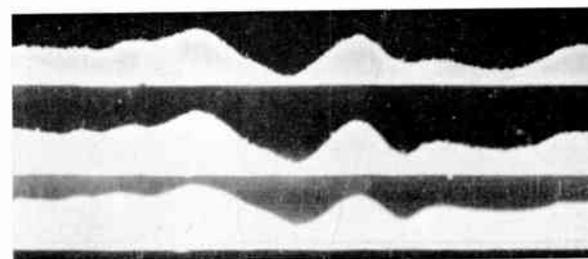
(*c*) F2 region, 7·8 Mc/s.

Fig. 3. Es and F2 spaced fading records 1400 hours, 29th June 1958.

1000–1400 and 2200–0300 hours I.S.T. Care has been taken to avoid taking records when Es is present sufficiently strongly that its fEs is nearer the operating frequency by about 1 Mc/s or less. About 150 pairs of records were taken but only about 60 records were found to be good enough for analysis. Examina-

tion of the results for these records has shown that except in a few records the drift speed is higher for the higher level. Such of those few records which gave higher drift speed at lower levels were not utilized in obtaining the average values of drift speeds for the two levels. The real height separation between the actual points of reflections was calculated by the Kelso[6] method for typical records taken during daytime and night-time hours of observation. The separation was found to be 30 km for daytime and 20 km for night-time. Using these values of separation between reflection points, and the average values of drift speeds for the two periods of observations, the drift gradients were calculated. They were 0·8 and 0·75 m/s per km of separation between the reflection points for the hours of 1000 to 1400 in daylight and 2200 to 0300 hours in night-time respectively. It is interesting to see that the gradient of drift speed between F1 and F2 regions was found to be 0·86 m/s per km for 0900 and 0·71 m/s per km for 1200 hours. All these values are in reasonable agreement with the only known value of 1 m/s per km obtained at Cambridge by Briggs and Spencer[7] using the spaced receiver method.

5. Conclusions

We summarize the results of the simultaneous study of drifts at two levels in the ionosphere as follows.

(1) F2 region drift speeds are always higher than F1 drift speeds measured simultaneously.

(2) F2 drift measurements are generally unaffected by drifts prevailing in the F1 region, except on a few occasions when f_0F1 value is very near the F2 operating frequency. On these few occasions F2 drift directions as well as drift speeds come out to be very nearly the same as those obtained for the F1 region.

(3) F2 drift measurements are unaffected by Es drifts, as long as the F2 operating frequency is higher than fEs by at least 0·8 Mc/s. If the difference in the frequencies is less, the F2 drift velocity is nearly the same as the Es drift velocity.

(4) The close agreement in drift velocities as well as the similarities in the fading pattern for records obtained when fEs is greater than the operating frequency suggests that on these occasions the fading on the signals reflected from the F2 region is superposed at the Es level.

(5) In the F2 region, the drift speed shows a definite increase with height at the rate of 0·8 m/s per km during daytime and 0·75 m/s per km during night-time.

6. Acknowledgment

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British Nuclear Power Stations

By

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(Associate Member)†

The Chairman's Introduction to the Symposium on "Electronic Instrumentation for Nuclear Power Stations" held in London on 29th March 1961.

Summary: The first experimental power stations are briefly referred to, mention being made of the development of a neutron flux measurement technique. The C.E.G.B. power station programme is described, reference being made to the instrumentation problems associated with Wigner energy storage and spatial instabilities in the reactors.

I should like to use this opportunity to review the history of nuclear power stations in this country and I think you will agree with me that the advances made so far are quite remarkable.

The story really starts with a conference which was held at Harwell in September 1950 to review the possibilities of getting power from reactors fuelled with natural uranium. Among the papers presented was one in which an engineer at Harwell gave new estimates of the cost of power generation from a gas-cooled reactor. The figure of less than a penny a unit was considerably lower than previous estimates and, although it provoked a great deal of discussion, was accepted as probably not far from the truth. Accordingly a team at Harwell was set up to see whether these early ideas could be converted into a feasible design. This team started work in January 1951 and later included engineers from the Central Electricity Authority and industry. The outcome of this feasibility study was the PIPPA reactor system, capable of generating more than 50 MW of electricity at less than one penny a unit.

In February 1953 the Government accepted a recommendation that a single PIPPA-type reactor should be built but optimized for plutonium production. A design team was set up at Risley which started work on the 7th April 1953 and this first reactor went critical on 22nd May 1956.

This was a remarkable project. I can remember that when we started, there were innumerable problems that just seemed to disappear after an initial bright idea and the detailed design work. As an example, I should like to quote the problem we were faced with in 1953 of measuring the neutron flux level right down to shut-down power levels. This we had decided was highly desirable from the safety point of view. We obviously could not put the necessary instruments inside the reactor—we probably could not do this successfully today. But we had 2 inches of steel in the form of the pressure vessel between the reactor

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core and the only feasible place where neutron detectors could be sited. The thermal neutron flux would be attenuated by a factor of several hundred and the pressure vessel would become radioactive, producing gamma rays that would interfere with the measurement of neutrons. In fact, the "signal-to-noise" ratio would be about 10^5 below the level at which neutrons could be measured. However, we realized that the fast neutrons would not be attenuated to any large extent by the pressure vessel. So if we could place a large block of moderator, such as graphite, outside the pressure vessel, we could thermalize these fast neutrons and measure the reactor power that way. In addition, some lead around the ion chambers could attenuate the gammas without affecting the neutron level. Such was the pace of construction that we had just two weeks to spare before the concrete of the biological shield had reached a level such that inserting the graphite block would have become almost impossible. Also at about the same time, we had discovered that the shut-down power of BEPO was unexpectedly high. This was due to the presence of some antimony–beryllium sources that had been inserted by the isotope production people. We calculated that if we could make some very large antimony–beryllium sources, we could increase the shut-down power of the Calder Hall reactor by a factor of about 1000. The combination of these three ideas solved that problem and these principles have been used on all subsequent reactors.

During the Calder Hall programme, as the design looked more and more encouraging, the number of reactors was increased to two and then four, all at Calder Hall, and then an additional four reactors at Chapelcross in Scotland, the last of these coming into operation towards the end of 1959.

A provisional programme of nuclear power for the United Kingdom was outlined in a White Paper published in February 1955. This programme provided for the construction, by the end of 1965, of twelve nuclear power stations with a total output of 1500–2000 MW. These stations would be built for the Electricity Authorities as part of their com-

mercial electricity supply network by private enterprise companies and were quite separate and distinct from the eight plutonium and electricity producing reactors at Calder Hall and Chapelcross. It will be seen that it was originally envisaged that the station size would be around 100 MW for two reactors, rising later to around 200 MW for a pair of reactors. This compares with about 70 MW net electrical output from a pair of Calder Hall reactors.

The first two nuclear power stations to be started under this programme were Berkeley and Bradwell. Both were started in January 1957 and are due for completion later this year. Berkeley will have a net electrical output of 275 MW and Bradwell 300 MW. These were followed fairly quickly by Hunterston in Scotland (328 MW) and Hinkley Point (500 MW). Then follows Trawsfynydd (500 MW) and Dungeness (550 MW) and work should start on Sizewell (580 MW) in April 1961. This brings the total nuclear power generating capacity to 3000 MW which is over 10% of the country's present generating capacity.

The design of the first four stations has not proceeded without any troubles being encountered. I should like to mention two that have had an impact on the instrumentation. The first is due to the property graphite has of storing energy—the so-called "Wigner energy". The accident to the Windscale reactor in October 1957 demonstrated that if this energy were released in an uncontrolled fashion, the results could be quite spectacular. This emphasized the need for modifying the design to reduce the amount of energy that might be stored and also emphasized the need for a considerable number of measuring points in the graphite structure, so that the temperature distribution could be readily ascertained.

The second arose from a theoretical prediction that, unlike all previous reactors in this country, these reactors will be spatially unstable. That is, the power distribution throughout the reactor will not be constant and stable, but if left to itself it wanders continuously. This has led to the incorporation of not just one automatic control system, but a number of systems, usually nine, spread throughout the reactor so that each control system looks after a particular zone of the reactor. In addition it has highlighted the need for knowing the temperature distribution throughout the reactor. Both the "Wigner energy storage" problem and the spatial instabilities have dictated the necessity for a data handling system dealing with temperatures from around 800 points throughout the reactor. The need for these was not fully appreciated until after the first four contracts were placed.

Where do we stand today? We have under construction (or nearly so) seven power stations totalling 3000 MW, more than $1\frac{1}{2}$ times the size of the original programme. The capital cost of these stations has fallen from £160 per kW for Berkeley and Bradwell to around £100 per kW for Sizewell. The size of the stations has risen from the 70 MW electrical output for a pair of Calder reactors to 580 MW for Sizewell. The thermal efficiency of the stations has risen from the 24·4% for Berkeley to the 32·9% of Dungeness. The cost of electricity generation depends very much upon such things as interest rates, amortization period and accounting systems; comparison between countries or between different types of power station is thus very difficult. However, using the most recent figures, it would appear that for the later stations the cost of electricity generation has fallen to a point where the cost will be competitive with a coal-fired station in that area. All these advances have been made before any of the stations have started operating. The pace of these developments demands high praise to all those engaged in this industry.

Background Factors to the Design of Control Equipment for the Civil Nuclear Power Stations

By

R. D. TROTTER, B.Sc.(Eng.)†

Summary: The design of the control and indication facilities required to supervise the equipment of a nuclear power station must be based on an appreciation of the methods of operation of the plant, and its staffing. The first nuclear stations are expected to operate at very high load factors as base load stations for the transmission system. This criterion leads to station layouts designed to use the minimum of staff on day-to-day operation and to the use for each station of a central control room. This paper outlines the principles governing the design of equipment for the C.E.G.B. stations and serves as an introduction to other papers of the Symposium which describe the instrumentation in detail.

1. Introduction

The specification for the Central Electricity Generating Board's first nuclear stations (Bradwell and Berkeley) was issued early in 1956. At the present time (March 1961) these two stations are on the point of being commissioned and a further four stations are in process of being constructed. In addition, a further station, Hunterston, is being constructed for the South of Scotland Electricity Board, and tenders are in course of preparation for a seventh C.E.G.B. station.

The electrical outputs of these stations represent considerable increases on that of the prototype reactors built at Calder Hall (and repeated at Chapelcross) by the U.K.A.E.A.

Station	Number of reactors	Station electrical output (megawatts)
Calder Hall (U.K.A.E.A.)	4	152
Chapelcross (U.K.A.E.A.)	4	152
Berkeley	2	275
Bradwell	2	300
Hunterston (S.S.E.B.)	2	328
Hinkley Point	2	500
Trawsfynydd	2	500
Dungeness	2	550
Sizewell	2	580
Oldbury	2	Not yet announced

† Central Electricity Generating Board, London, S.E.1.

The total capacity of the first six C.E.G.B. stations therefore amounts to 2705 megawatts nett electrical output.
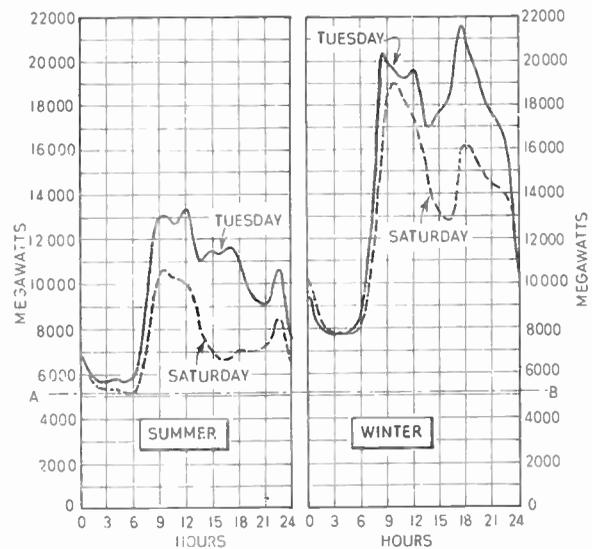
Fig. 1. Typical daily load curves, summer and winter 1959–60.

Figure 1 shows typical daily load curves of the C.E.G.B. system. The present (1960–61) winter peak load of the C.E.G.B. system is in excess of 22 000 megawatts and the lowest system load occurring during a night in summer time is of the order of 5000 megawatts. Each of these load figures increases by about 7% per year. So it can be seen that the total nuclear generation, although considerable in itself, forms a small proportion of the system capacity.
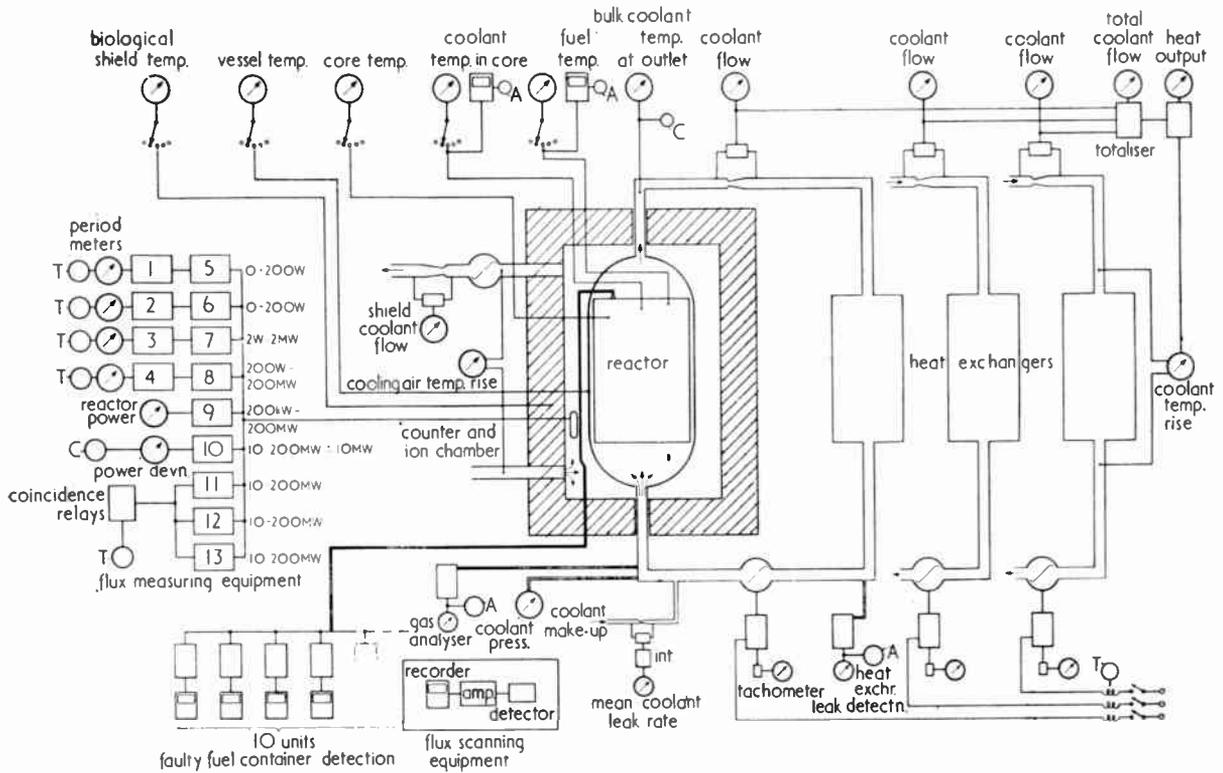
Fig. 2. Schematic diagram of essential instrumentation of a graphite-moderated gas-cooled power reactor.

The overall generation cost of the latest nuclear stations is very close to that of the latest coal-fired stations but with a different emphasis. In the case of a nuclear station, about three-quarters of the overall cost per unit generated is caused by initial capital cost and one-quarter by replacement fuel costs. These proportions are reversed for coal stations.

Thus having once built the nuclear stations, the Generating Board have a very strong incentive to maintain their output as high as possible for as long as possible, since if taken off load the generation will have to be replaced by coal-fired plant at a much higher fuel cost per unit. This method of operation is referred to as "base load".

This situation is expected to continue for the stations now being built even if more advanced nuclear stations are designed having a lower overall generation cost. The greatest reductions in overall cost will come from reductions in capital cost, and fuel costs may not decrease very much, and may even increase if enriched fuel has to be used. Only if irradiation times of more advanced fuel can be increased by factors even greater than those anticipated will this general statement have to be modified.

Therefore, when considering the design of control systems for the C.E.G.B. stations, one can start from the point that these are base load stations and will

remain so throughout their lives. This criterion leads to a station designed for a very small number of staff for day-to-day operation and to the use of a central control room, co-ordinating all control activities of the reactors, turbines and electrical systems.

2. Features of Overall Plant Control and Instrumentation

Figure 2 shows a schematic diagram of the essential instrumentation of a graphite moderated reactor.

For safety in operation, it is obvious that adequate control of the reactors and plant must be available, and the instruments of a central control room grouped to present a clear overall picture of plant behaviour to the operators.

Safety demands control of three main aspects:

(i) That the heat output of the reactors should always be removed and consumed. Normally this heat is absorbed by the boiler systems, passed on to turbines and thence from alternators to the transmission system.

(ii) That reactor temperature conditions are maintained satisfactorily. The temperature T_1 of gas entering the reactor after passing through the boilers is more or less naturally constant, and is a function of steam and feed water

conditions. For convenience in operation and to enhance fuel life, the reactor gas outlet temperature T_2 is also maintained constant. Thus the power level of the reactor is mainly varied by varying the mass flow of cooling gas going through the core, and the thermal output will be a function:

heat = rise in temperature $\times$ mass flow of gas.

(iii) That the power created in the reactors, which is mainly a function of the number of fissions occurring per second, can be raised to operating value, maintained constant at any desired level, and shut down whenever required. This is done by the withdrawal and insertion of neutron absorbing material from and into the reactor core.

3. General Layout

The location of the central control room in relation to the reactor buildings and turbine room should be such that it is immediately accessible from both places and therefore a position between the reactor buildings and turbine room is chosen. In the first nuclear stations the central control room was sited near to the turbine room, following certain traditions in conventional station design. Whilst this has a slight advantage from the operational point of view, the economies in cabling which can be achieved by locating the control room close to the reactor area, are such that in the later nuclear stations the control room is sited adjacent to the reactor buildings. In order to provide free access to the control room, it is located in a "clean condition" area and staff proceeding from the control room to the reactor operational areas have to pass through a "main change room".

In the earliest stations no access to open windows or natural lighting was provided and whilst this had advantages from ease of illumination and in ensuring an atmosphere free from outside distractions, there is a body of opinion which feels that some attempt should be made to reduce the feeling of enclosure which will be experienced in control rooms of this nature. Difficulties occur in providing windows in view of the location of the control room and the necessity of keeping radiation levels low in a position which is continuously manned. This later requirement is however somewhat eased in the later nuclear stations due to the improved shielding which is being provided, and it is considered that some attempt should be made to overcome this sense of remoteness by the suitable positioning of windows, doors and roof lights. The main difficulties to be overcome in such a case will be with avoiding variations in visibility of instruments when natural light values change, the positioning of the panels in relation to windows and doors and also ensuring complete safety of the control

room during major plant accidents. It is also important to ensure that noise levels are kept as low as possible, and that the heating and ventilation plant meets this requirement.

4. Staffing of Control Room

The staffing of nuclear stations has developed much on the lines of conventional stations, and the basis of design has been that all plant will be supervised locally by plant operators and attendants. They will be responsible for local starting and will hand over plant to the control room staff for subsequent minute-to-minute operation.

There will be three main operators on shift in the control room. Each reactor will have one operator who will be of technical staff grading. It is intended that the stations will have three engineers who will interchange duties on a regular basis between the turbine room, reactors and central control room. One of these engineers is therefore considered as the control room supervisor. These decisions reflect on the way in which the central control room is designed.

The layout of equipment in the central control room should assist a status of the supervisor who is expected to act as the main channel of communication to senior station staff, and for operation matters outside the station. He may be expected to inspect personally alarm indications received in the control room, and also to carry out the operations associated with major plant changes. In addition, control of the 275 kV electrical panel together with the generator synchronizing equipment will be the responsibility of the supervisor.

Each reactor operator is therefore provided with a control desk, and it is assumed that they will stay at their desks during all normal operations. Telephone communication from these desks is provided to all operational points and these are duplicated on the supervisor's desk together with the instruction panel associated with the grid control centre.

5. Central Control Room Panel and Desk Structures

Since the number of indications and control required in the central control room is very large, the considerations of staffing of this room have led to a basic design consisting of a desk for each reactor operator and vertical panels in front of these desks. The operators at the desks should be able to follow and control reactor conditions during start-up and normal running, without moving to the vertical panels.

The vertical panels have those controls and indications which are associated with individual plant items and also have over-riding controls and delegation switches provided in order that the control room staff

can take immediate action in the event of any emergency arising. The arrangement of the vertical panels include separate sections for each boiler containing instrumentation for h.p. and l.p. steam conditions, feed and gas flow indications and controls. In the earlier stations with their larger number of boilers this has resulted in a quite extensive block of identical instrumentation which makes it difficult to identify a particular instrument. With the later stations the reduction in number of boilers has simplified this problem but it is important to ensure that simple and clear layouts are adopted. This could be achieved by a departure from individual boiler panels and adopting a functional arrangement of individual indications for all boilers together but this idea has not yet been pursued since the indications are primarily required during plant emergencies.

The stations are designed for range operation on the feed water, steam and electrical systems. Thus the unit and station auxiliary electrical supply board are interconnected in normal operation to provide stand-by facilities to each other. The main steam systems are interconnected by pipework enabling the reactor outputs to be shared in varying proportions between all the turbines in the station. It is possible, however, to operate with each reactor and its associated turbines as a unit if experience shows this to be desirable, or during special conditions. Range operation introduces some interaction between the two sets of plant, but when turbine or reactor trips take place, more of the plant can be maintained running although at a reduced load. Also less investment of reactivity in the reactors is required for poison over-ride purposes which result in a more economic design.

Normal conditions in the station demand that the turbine heat consumption is matched at all times to the reactor heat output. A typical figure on this point is that 1% increase in turbine load sustained for one minute without alteration to reactor output, will change steam pressure conditions by about 1%.

These factors have led to designs for the first stations in which there is one control desk for both reactors with the turbine controls placed between sections of the same desk dealing with each reactor. The resulting structure of a single unit combining both reactors and turbines becomes very large and in the design the major controls of power and temperature used in normal running are grouped towards the centre section as far as possible. The problem of reducing the size of the desks could be achieved by the use of 50 volt control circuits in place of the standard 110 volts used at the present time. This would lead to smaller control handles and the elimination of heavy wiring. In addition, considerable saving in space could be accomplished by the adoption of 4-in. recorders in place of the standard 10-in. now in

use. These ideas will be put into practice as soon as the design features of 50 volt apparatus required for adequate security in these important duties have been thoroughly identified.

6. Controls and Indications Used at Full Power

These facilities should be given priority in the layout of equipment because they are in use for the great majority of time. The balance between turbine heat consumption and reactor heat output is maintained by manipulating the turbine governors and the coolant flow controls of the reactor with a critical steam pressure gauge as a balance indication. The minute-to-minute variations of these parameters is a function of frequency variation on the grid system and the limited ability of the reactor fuel elements to stand thermal cycling. The best operating techniques remain to be evolved as a result of operating experience.

The control of reactor heat production depending as it does on the movements of control rods demands an intimate display of the core neutron population and this is most easily provided by an ion chamber mounted external to the pressure vessel and giving a reading which is a direct ratio of the total neutron population. This ratio is roughly constant throughout the upper power ranges. The instrument used for minute-to-minute control has a backed-off scale, and has the further advantage fundamental to measurements of neutron population, rather than of temperature effects, of a very quick response time.

Summing up the indications and controls which are grouped together as closely as possible in the normal operating position, they are:

  Backed-off neutron power
  Fuel element temperature
  Gas outlet temperature
  Reactivity control
  Turbine governor control
  Reactor coolant mass flow control
  Critical steam pressure indication.

7. Automatic Control

At all stations the main reactor gas outlet temperature conditions are controlled automatically. To combine this function with the control of localized flux changes, the reactors are provided with several (usually nine) independent control loops each of which monitors one sector of the reactor in plan view. This operates on a single control rod centrally placed in the appropriate sector from averaged thermocouple readings of channel gas outlet temperature in that sector. These loops will adjust automatically for changes in fuel, although some trimming of the sector rod positions by moving selected bulk rods will be

required at infrequent intervals, say once a week. The presence of these control loops also is a major aid to reactor safety since they act in unison with correct temperature conditions following major plant interruptions. At the same time, since the reactivity invested can be moved at high rates it is limited in value and the individual sector loops are made as independent from one another as possible. With irradiated fuel and a positive moderator temperature coefficient of reactivity, it is thought that operation of the reactor with one of the independent sector loops out of action will not be too inconvenient, and operation with two of the loops out of action will also be possible. In these circumstances, the sector rods of those sectors not on automatic control will require manual adjustment from the individual vertical panels concerned at infrequent intervals, say once every half hour. For this reason and also in view of the importance of the sector rod systems the individual sectors are each given a vertical panel with individual indication of sector rod position and sector temperature, and these panels are placed in those parts of the main panel runs most easily reached by the control room supervisor, or alternatively by the reactor desk operators.

The load on the transmission system is constantly varying, as the customers switch on and off many thousands of individual loads. All generators connected to the grid system have steam governors sensitive to system frequency, and these act to preserve system stability for very short term variations, longer term variations being controlled by the system control engineers who dictate to individual stations the average power to be generated for the next appropriate period of time. These engineers raise or lower the generation at individual stations to follow predictions of the load curve based on previous experience and on various weighting factors such as the weather conditions or economic factors of the level of industrial activity, etc. The stations are loaded so that the most expensive stations in terms of unit fuel cost are loaded last and taken off load first.

A further advantage of this system of "speeder gear" governing is that system frequency is preserved at time of major dislocation of parts of the grid system through transmission line faults, etc.

This policy is therefore continued for the nuclear stations so that they may make an appropriate contribution.

Since the stations are expected to operate as "base load", and since too sensitive adjustment of reactor power output to follow grid frequency variations might be inadvisable, automatic control of reactor power output by operating on mass flow of coolant is not really essential and is not provided at Berkeley or Hinkley Point. However, equipment is provided for

Bradwell and will be provided for all stations from Trawsfynydd onwards. This has been decided in order to gain experience in the use of this facility which may also be most useful to the operators during start-up conditions or major load changes, or at times of plant trouble. Also future developments in the supply system may mean that nuclear stations have to be used for frequency regulation and it has been thought prudent to supply the equipment intimately associated with the station design from the start. The experience gained on the effects of thermal cycling on fuel elements will effect the closeness of control of power output which can be used. In any case thermal cycling is inevitably introduced by fuel changes, the actions of charging and discharging fuel which change the reactivity of the core slightly with each operation, especially as the mechanisms inserted to remove fuel are themselves absorbers of neutrons.

In the layout of control room equipment, the automatic control loops are assumed to have a very high availability although this may prove not to have been achieved in the present state in the art of manufacturing electronic equipment. It is recognized, however, that it must be possible to run the stations without automatic control loops available, and that the reactor operators should be able to take the automatic loops out of action from the main control desks.

8. Plant Occasions which require Urgent Action from the Central Control Room

Many plant occurrences, for example failure of a single feed pump, or some occurrence on the circulating water system, do not require direct action from the control room. Some occurrences, however, do result in control room action and an analysis of the sequence which occurs is necessary to determine the controls and indications required and their relative layout.

For example:

(1) *Reactor Trip.* In this case it is important that the control room can quickly ascertain the cause of the trip and whether the auxiliary system electrical supply has failed or not. If electrical supply failure has occurred, the essential supply system will take over automatically those reactor auxiliaries required for safety.

(2) *Loss of Grid Connections.* This will result in a loss of outlet for power from the station, but the turbines should continue to run, supplying the station auxiliary system and the excess power will lift the boiler safety valves. Conditions can be stabilized at a lower power level and if the grid power circuits can be restored to service quickly, the reactor output can be increased again before poisoning causes reactor shutdown. For stations with a considerable local load, it

may ease the situation if one reactor is tripped and the range operation of the station used to avoid shutting down the turbines immediately.

(3) *Turbine Trip.* This occurrence will call for a reduction in reactor power by coolant mass flow reduction, but again if the station is operating ranged, the effect on the reactors can be reduced.

(4) *Circulator Trip.* The temperature transients which follow a single circulator failure on a reactor, are not such that reactor tripping is produced. The turbine outputs must be reduced to match the new reactor power conditions.

9. Control of Station during Reactor Start-Up

During start-up the reactor operators should have sufficient indications to supervise the reactor conditions from the operating desk, although it is assumed that there will be extra staff available in the control room during start-up, and these will be available to observe more detailed monitoring indications given on the vertical panels.

In assessing the facilities required, some of the factors that are taken into account are:

> start-up may be on a limited number of boiler circuits;
>
> the control rods are operated in several groups;
>
> period protection is used to control approach to criticality, and some time thereafter;
>
> the rate of rise of gas inlet temperature has to be observed;
>
> the rate of rise of gas outlet temperature from the reactor has to be controlled;
>
> gas flow conditions between various boiler circuits may have to be balanced.

10. Conclusion

This paper has attempted to outline the considerations of plant requirements and staffing which govern the design of the control rooms for the first civil nuclear power stations. It is not yet possible to judge whether a completely successful design has been achieved.

The future progress of the civil nuclear programme may call for more highly rated reactors in which the time-constants of control circuits will be shorter than at present. The stations may also assure such a proportion of the system load that they are no longer designed on the present base load concept.

The designer of control equipment must always be conscious of the challenge to produce automatic control and sequence control systems which are more consistent, reliable and safe than the present control loops using human operators.

This challenge is being anticipated for the Oldbury design of the C.E.G.B., which will incorporate a greater degree of centralized control in that all plant operations during starting-up, load variation and shutting down of plant will be carried out from one control point. Limited sequence control of some auxiliaries will also be used.

However, present automatic techniques too often employ electrical or mechanical relays and other components which although of high reliability are less than perfect.

The author hopes, therefore, that by the time a fully automatic nuclear power plant is needed and justified, automatic control, by the ever-increasing use of solid-state switching techniques and transistors, will have developed to near perfect reliability. If the reliability of control circuits and instruments can be raised to a level considerably in excess of that of the mechanical plant being controlled, the present reluctance to trust light-current equipment on the part of the operator will disappear, and the expense and inconvenience of supplying manual control facilities in addition can be avoided.

Some Thermal Considerations on the Use of Solar Cells in Space Vehicles

By

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Summary: The dependence of solar cell characteristics on temperature is demonstrated. The radiation balance of solar cells in space is then discussed for different configurations of the cell assembly and for different orbits and it is shown that these can have considerable influence. Means of achieving temperature stabilization are described. The value of surface coatings is discussed briefly.

1. Introduction

Before we can usefully discuss the importance of temperature on the performance of a silicon solar cell it is necessary briefly to describe the basic physical mechanisms involved.

Incident photons of energy greater than the energy gap will be absorbed by the semi-conductor, and their energy will break valence bonds and promote electrons to the conduction band, thus producing free electron-hole pairs. Excess minority carriers on both sides of the junction will diffuse to the junction provided they were originally produced within a diffusion length or so of the junction. This process is illustrated in Fig. 1.

Those carriers reaching the junction will be swept across it by the built-in electrostatic field, current flowing in the conventionally reverse direction, of the diode. If under short circuit conditions the resulting current flow is I_s, then in general a voltage will build up in the forward direction given by the normal diode equation,

$$I_f = I_0(e^{\lambda V} - 1) \qquad \ldots\ldots(1)$$

The net current I is the algebraic sum of I_f and I_s, that is

$$I = I_0(e^{\lambda V} - 1) - I_s \qquad \ldots\ldots(2)$$

This equation can be simply modified to allow for an internal series resistance r_s giving

$$I = I_0\{\exp(\lambda V - Ir_s) - 1\} - I_s \qquad \ldots\ldots(3)$$

The working point on this (I, V) characteristic is determined by the external circuit: under open circuit $I = 0$, so

$$V_{oc} = 1/\lambda \log(I_s/I_0 + 1) \qquad \ldots\ldots(4)$$

According to simple theory, $\lambda = e/kT$ and I_0 is the diffusion limited reverse current. In practice however, we must write

$$\lambda = \beta e/kT \text{ where } 1 < \beta < 5 \text{ and } \beta = \beta(I)$$

and I_0 is many orders of magnitude larger than that predicted by simple theory, being principally due to

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the generation of carriers at deep levels in the space charge region.

The maximum power P_{max} available with optimum load cell can be determined from the I-V characteristics, (3). It is often useful to define a form factor s so that $P_{max} = sV_{oc}I_s$.
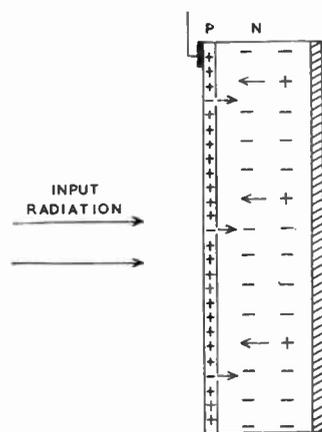
Fig. 1.
Solar cell operation.
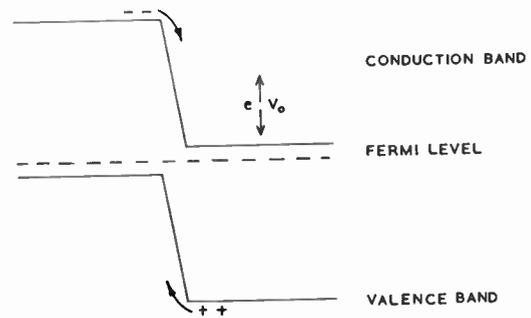
2. Temperature Dependence of Solar Cell Characteristics

In Fig. 2 are shown typical I-V plots as a function of temperature. The increase of current with temperature is due to the move of the absorption edge to longer wavelengths as the temperature increases, thus

allowing a larger fraction of the incident photons to be usefully absorbed. This effect is more marked in such laboratory tests as these with a light source of low colour temperature ($\sim 2800^\circ$ K) than it would be in practice with the sun ($\sim 6000^\circ$ K). The inverse dependence of V_{oc} on temperature is largely due to the temperature dependence of I_0.

It can also be seen that for power matching the optimum load is a function of temperature. The problem can be simplified by neglecting power matching and considering only the available current to charge a secondary cell at a particular voltage, V_c. Even in this case, however, since V_{oc} can vary between say 450 mV at 100° C and 700 mV at -26° C then if
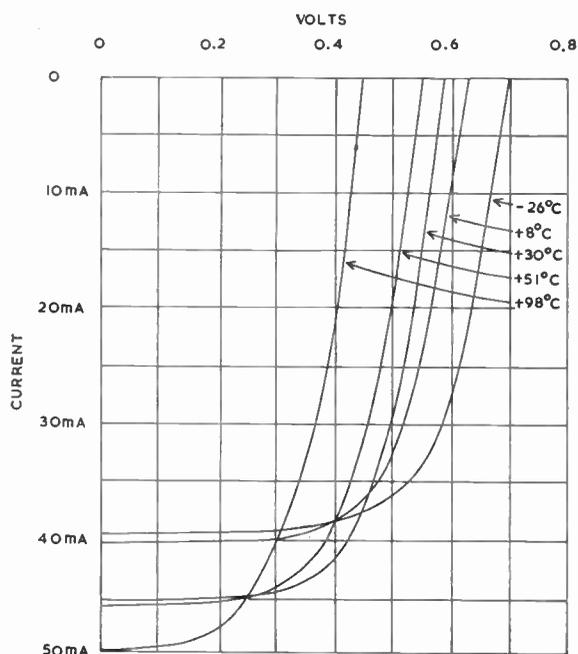
Fig. 2. Current-voltage characteristics of a solar cell as a function of temperature.

V_c is say, 600 mV then one cell will only deliver charging current when its temperature is 20° C, and for higher temperatures two cells will be needed in series. Now, however, except at the highest temperatures there will be excess voltage wasted, and the maximum charging current is only that appropriate to one cell.

It is fairly obvious therefore that the number of solar cells required to give a guaranteed charging current (and hence the weight and cost of the system) is strongly dependent on the temperature cycle of the assembly when in orbit. Accordingly we now consider likely maximum and minimum temperatures, and methods of reducing the swing.

3. Radiation Balance of Solar Cells

The temperature reached by solar cells in space is determined by the radiation balance between the heat input from the sun and planets (direct and reflected radiation) and the heat loss to the surroundings, either directly or by conduction to another surface.

Solar cell clusters will be considered in two forms: as a double-sided plate, i.e. a plate both sides of which are covered with solar cells, and as a single-sided plate, the reverse side having characteristics such as to ensure as low a temperature as possible. Implicit assumptions present in the expression to be presented for the temperature of the solar cell are that the thermal conduction within the plate is high and that operation of the solar cell never takes place in the shadow of the satellite which subtends a negligible solid angle to the plate.

For a plate in space, free from the influences of planets, the normal making an angle θ with respect to the direction of the sun's radiation, the temperature, T, of the plate is given at thermal equilibrium as

$$A\alpha S \cos \theta = A\sigma(T^4 - T_0^4)(\bar{\varepsilon}_1 + \bar{\varepsilon}_2) \quad ......(5)$$

Here S is the energy incident per unit area at a distance d from the sun, the solar constant. If the sun is assumed to be a black body of radius r and temperature T_s, the solar constant is given as a function of distance by

$$S = (r^2/d^2)\sigma T_s^4 \quad ......(6)$$

σ is Stefan's constant.

α is a factor giving the proportion of the incident sun's energy, incident on a solar cell surface, which is converted into heat. It is given by

$$\alpha = 1 - \bar{R} - \bar{E} \quad ......(7)$$

$\bar{R}$ is the normalized reflectivity, that is

$$\bar{R} = \frac{\int_0^\infty R(\lambda,T)H(\lambda,T_s)\,d\lambda}{\int_0^\infty H(\lambda,T_s)\,d\lambda} \quad ......(8)$$

where $R(\lambda,T)$ is the reflectivity of the solar cell surface at normal incidence at a wavelength λ and at a temperature T, and $H(\lambda,T_s)$ is the energy from the sun at temperature T_s of wavelength λ.

$\bar{E}$ is the measured efficiency,

$$\bar{E} = \frac{\int_0^\infty [1 - R(\lambda,T)]P(\lambda,T)H(\lambda,T_s)\,d\lambda}{\int_0^\infty H(\lambda,T_s)\,d\lambda} \quad ......(9)$$

$P(\lambda,T)$ is the proportion of the absorbed energy of wavelength λ which is converted into electrical energy,
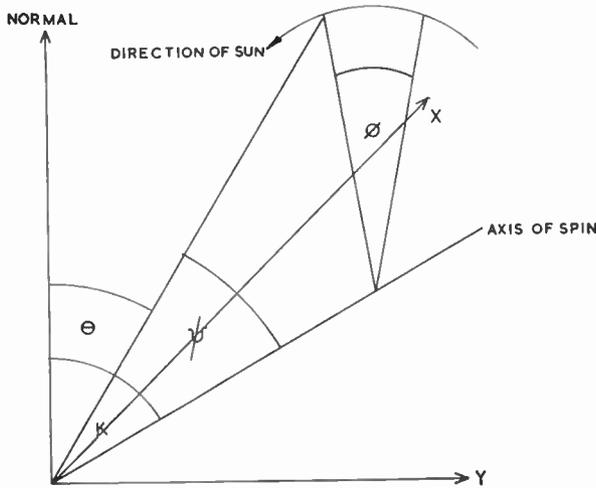
Fig. 3. Orientation of a spinning paddle.

the temperature of the solar cell being T.

$\bar{\varepsilon}_1$ and $\bar{\varepsilon}_2$ are the integrated emissivities for the two sides of the plate.

$$\bar{\varepsilon} = \frac{\int\limits_0^\infty \varepsilon(\lambda,T)H(\lambda,T)\,\mathrm{d}\lambda}{\int\limits_0^\infty H(\lambda,T)\,\mathrm{d}\lambda} \qquad ......(10)$$

$\varepsilon(\lambda,T)$ is the emissivity and $H(\lambda,T)$ is the energy emitted by a black body at a wavelength λ and temperature T.

A is the area of one side of the plate and T_0 the background temperature.

When the satellite is near to a planet, which in most cases will be the Earth, allowance has to be made for energy reflected by the planet on to the back surface of the plate. The planet also occupies a large part of

the solid angle subtended at the plate and its temperature must be taken into account as that of the background. If the plate is spinning integration must be made over the angle of spin, remembering that the reflectivity is a function of the angle of incidence. The heat input from the sun is then given by

$$\frac{Q}{AS} = \frac{\int\limits_0^\infty \int\limits_0^{2\pi} [1 - R(\theta,\lambda,T)]\,[1 - P(\lambda,T)]H(\lambda,T_s)\,|\cos\theta|\,\mathrm{d}\lambda\,\mathrm{d}\phi}{\int\limits_0^\infty \int\limits_0^{2\pi} H(\lambda,T_s)\,\mathrm{d}\lambda\,\mathrm{d}\phi}$$

......(11)

$$\cos\theta = \cos\psi\cos\kappa + \sin\psi\sin\kappa\cos\phi$$

where ψ is the angle between the direction of the sun's radiation and the axis of rotation, κ is the angle between the axis of rotation and the normal to the plane of the plate and ϕ is the angle of rotation about the axis (Fig. 3).

Values of the temperatures reached by the plate are given for certain conditions in Table 1. The mean temperature referred to is that temperature which the plate would reach if it had a large thermal time constant compared with the time period between maximum and minimum thermal equilibrium temperatures.

Assumptions made in obtaining the values shown are that the reflectivity $R(\theta,\lambda,T)$ is independent of angle of incidence, wavelength and temperature in the spectral region considered, i.e. up to $1\cdot1\ \mu m$, the long wave limit for a silicon solar cell. The justification for assuming the reflectivity to be independent of wavelength is given in Fig. 4, where the reflectivity of both components of polarized radiation, together with the total, is plotted as a function of angle; surfaces of optically polished silicon and of glass are considered for $0\cdot6\ \mu m$. For surfaces with interference
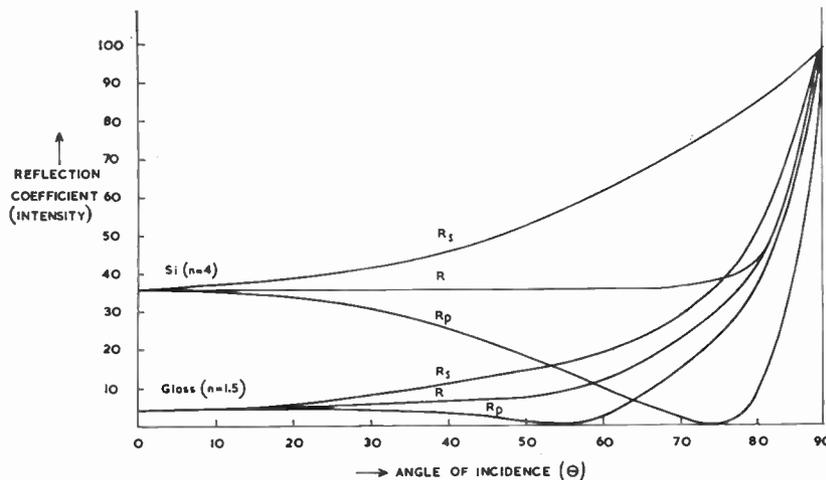
Fig. 4.

Reflection coefficient of silicon and glass as a function of the angle of incidence at $0\cdot6\ \mu m$.

films this will not be true. It can be seen that only at extreme angles of incidence does the total reflectivity differ appreciably from the value at normal incidence. This approximation is not valid when $\kappa + \psi$ approaches 90 deg. For conditions where the axis of rotation is in the plane of the plate and $\psi = 90$ deg and the plate is uniformly spinning the mean heat input from the sun is given by

$$Q = 2/\pi \ AS(1 - \bar{R} - \bar{E})$$

The temperature values were obtained assuming values, for a silicon solar cell with a cover glass intimately held over the surface (to avoid the "greenhouse" effect), of 10% for the integrated reflectivity $\bar{R}$, 0·9 for $\bar{\varepsilon}$ for a solar cell surface and 0·95 for the reverse, and an electrical efficiency of 10%. The earth is assumed to behave as a black body of 0° C regarding radiation to and from the plate and as a reflector of 35% of the sun's radiation.[1] The solar constant was taken from Johnson[2] as 0·140 watts per square centimetre, being taken at a distance equivalent to the mean distance of the earth from the sun. The radiation reflected from the earth may be of different spectral distribution and fall at a different angle on to the plate from that of the sun and account must be taken of this in integration. Values computed in Table 1 assumed the spectral distribution of the radiation falling on the plate after reflection to be the same as that from the sun. The orbit assumed was one in which equal times were spent by the plate in

the sun's radiation and in the shadow of the earth and the earth occupies half the solid angle seen by the plate, i.e. the orbit is close to the earth.

4. Temperature Cycling in Near Earth Orbits

When solar cells are used in near-earth orbits they undergo a temperature cycle associated with their passage through the earth's shadow. The temperature variation is related to the time constant of the mountings, as well as the equilibrium temperatures which would be achieved if the cells remain permanently in the light or in the shadow, which we designate T_L and T_D, respectively.

Suppose that the cells are mounted in a plate of thickness w, specific heat C, density ρ and emissivity $\bar{\varepsilon}$ when the heating and cooling of the paddle is described by the equations

$2\bar{\varepsilon}\sigma(T_L^4 - T^4) \, dt = C\rho w \, dT, \ T < T_L,$ in the light
$2\bar{\varepsilon}\sigma(T_D^4 - T^4) \, dt = C\rho w \, dT, \ T > T_D,$ in shadow

$$......(12)$$

Neglecting the temperature variations in the parameters these equations may be integrated to yield

$t/\tau_L = |\tan^{-1}(T/T_L) + \tanh^{-1}(T/T_L)|$ in the light
$t/\tau_D = |\tan^{-1}(T/T_D) + \coth^{-1}(T/T_D)|$ in shadow

$$......(13)$$

where $\tau_D = Cw/4\bar{\varepsilon}\sigma T_D^3$ etc.

These relations have been computed and are conveniently rewritten as

Table 1

Condition	Radiation Balance for Maximum Temperature	Maximum	Minimum	Mean
Single-sided plate oriented normal to the sun's radiation in space	$T^4 = \dfrac{\alpha S}{\sigma(\bar{\varepsilon}_1 + \bar{\varepsilon}_2)}$		321° K (48° C)	
Double-sided plate spinning about on axis normal to the sun's radiation in space	$T^4 = \dfrac{\alpha S}{\pi \bar{\varepsilon} \sigma}$		228° K (15° C)	
Double-sided plate oriented normal to the sun's radiation near the earth	$T^4 = \dfrac{1 \cdot 35\alpha S}{2\bar{\varepsilon}\sigma} + \dfrac{T_E^4}{2}$	377° K (104° C)	230° K (−43° C)	337° K (64° C)
Double-sided plate spinning about on axis normal to the sun's radiation near the earth	$T^4 = \dfrac{1 \cdot 35\alpha S}{\pi \bar{\varepsilon}\sigma} + \dfrac{T_E^4}{2}$	349° K (76° C)	230° K (−43° C)	318° K (45° C)
Sphere in space	$T^4 = \dfrac{\alpha S}{\pi \bar{\varepsilon}\sigma}$		288° K (15° C)	
Sphere near earth	$T^4 = \dfrac{1 \cdot 35\alpha S}{\pi \bar{\varepsilon}\sigma} + \dfrac{T_E^4}{2}$	340° K (76° C)	230° K (−43° C)	318° K (45° C)

$$\log T = f_L(t/\tau_L)$$
$$\log T = f_D(t/\tau_D) \qquad \ldots\ldots(14)$$

where f_L, f_D are heating and cooling functions related to those defined earlier. These curves are shown in Fig. 5.

We now insert the condition that the paddle has reached dynamic equilibrium. If T_d is the temperature in Fig. 5a when the satellite has just passed over the shadow, then after the half period τ_0 of the satellite it will be re-entering the shadow and the temperature has reached T_l; if the paddle has reached equilibrium

of τ_0/τ_D. These pairs of values are shown in Fig. 6 for $T_L = 94^\circ$ C and $T_D = -43^\circ$ C. If we insert values for the constants say

$$\tau_0 = 45 \text{ minutes}, \ C = 0\cdot21, \ \rho = 2\cdot7, \ \bar{\varepsilon} = 0\cdot7,$$
$$\sigma = 1\cdot37 \times 10^{-12} \text{ thermal c.g.s.u.}$$

we can plot T_l and T_d against w. The constants are appropriate to an aluminium plate covered with solar cells. About half the weight is required for the same excursion if beryllium is used. The thicknesses necessary for good temperature stabilization are however well above those required for mechanical strength so the designer must pay a weight penalty which must be
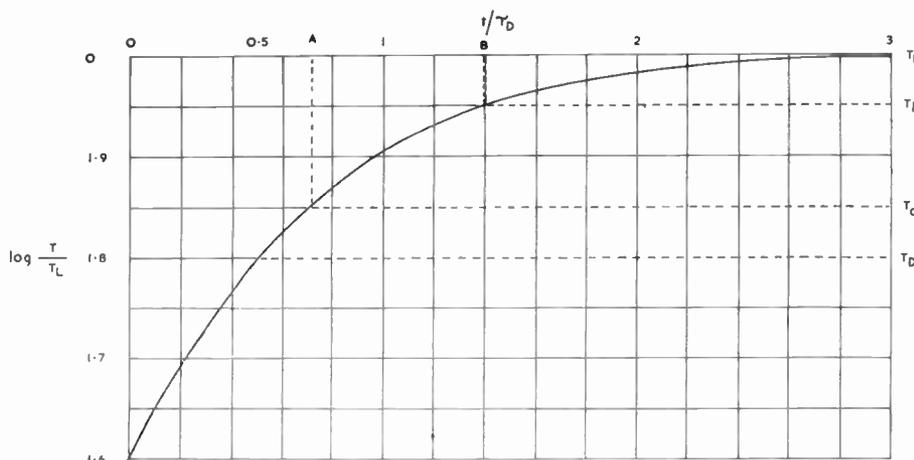
Fig. 5.
Temperature cycling of paddle

(a) Heating curve

(b) Cooling curve.
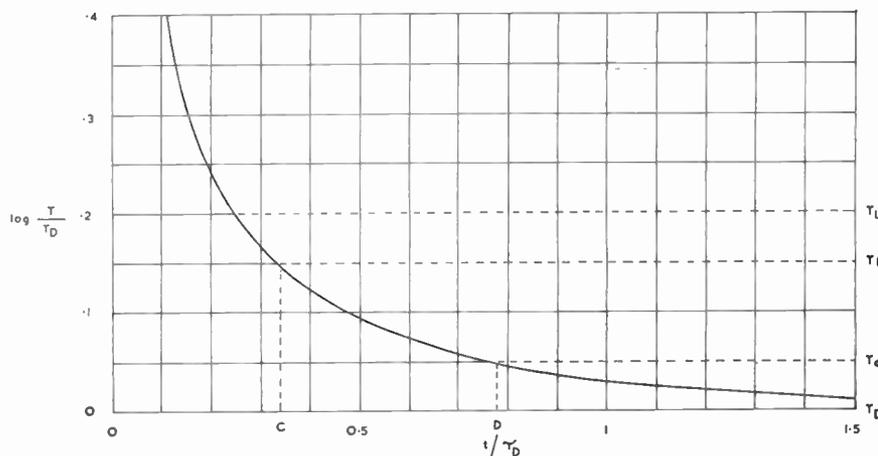
the temperature will fall to T_d during the half period while this is in shadow again. Allowing for the scale-factors on the time axes, this implies

$$\frac{AB}{CD} = \frac{\tau_D}{\tau_L} = \left(\frac{T_L}{T_D}\right)^3 \qquad \ldots\ldots(15)$$

This condition is obtained by replotting the cooling curve with the time scale stretched in the ratio $(T_L/T_D)^3$ and with the sense of t reversed. The intersections of this curve with Fig. 5 give pairs of possible values for T_d and T_l associated with different values

assessed in relation to the orientation and power requirements of any given satellite.

It is interesting to see that almost complete temperature stabilization can be achieved without such a large weight penalty by using latent heat of fusion. The period of arrest t obtained with a paddle of area A containing M grammes of material of latent heat L and melting point T_m is given by

$$ML = 2\bar{\varepsilon}\sigma A(T_L^4 - T)t_m^4 \qquad \ldots\ldots(16)$$
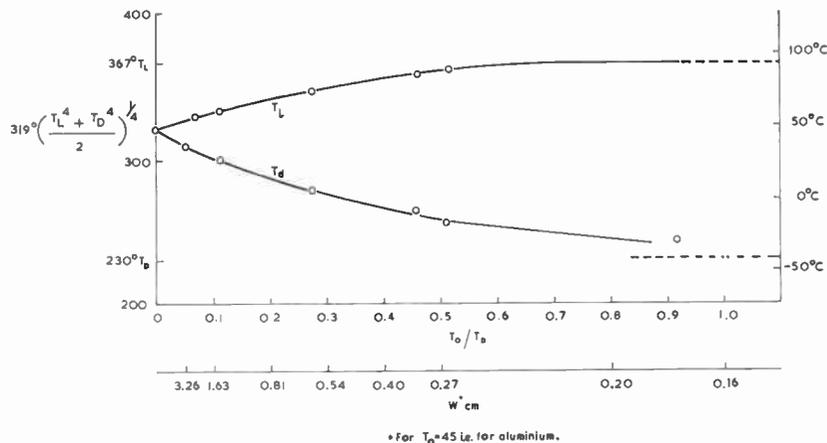
Fig. 6. Variation of the maximum and minimum temperatures reached with ratio of the satellite period to thermal time constant.

Thus the mass required per unit area is

$$2\bar\varepsilon\sigma(T_L^4 - T_m^4)\tau_0/L \qquad \ldots\ldots(17)$$

T_m must be greater than $\{(T_L^4 + T_D^4)/2\}^{\frac{1}{4}}$ if the liquid is to freeze completely during the period in the shadow. Suitable materials of high latent heat include the fatty acids and some hydrated salts, such as

Stearic acid   m.p. 64° C   47·6 cal/g

Elaidic acid   m.p. 47° C   52·1 cal/g

Dibasic sodium phosphate

    (decahydrate)   m.p. 36·1° C   66·8 cal/g

Again using the value $T_L = 94°$ C and $T_D = -43°$ C, $\bar\varepsilon = 0·7$, the amount of elaidic acid for stabilizing at 47° C is 0·76 g/cm² of surface (one sided). This sort of complete temperature stabilization has the advantage that not only is the mean temperature of operation reduced, but the elimination of fluctuations allows the solar cells to be exactly matched to the charging voltage of the battery throughout the half-period in the light. Thus the total number of cells needed is substantially reduced.

If the latent heat of vaporization is used still further reductions in the weight penalty are obtained, which must be offset against the complications involved in providing a cavity into which the vapour of the boiling liquid can escape. The obvious liquid to use is water with its high latent heat (572 cal/g at 47° C) of which only 0·069 g/cm² are required, boiling at 47° C and 80 mm pressure. The water requires an expansion chamber of 820 cm³ capacity per cm² of paddle surface at this pressure.

5. Ideal Surface Coatings

One way of reducing the temperature extremes to which a solar cell assembly may be subjected is to produce more desirable optical properties than those of a simple silicon surface. In Fig. 7 are shown the spectral distribution of the sun's emission and of the solar cell response.

From these curves it can be seen that only radiation of wavelength, λ, given by $0·4 < \lambda < 1$ μm is usefully incident. Any radiation outside this range (as well as

Fig. 7.

Solar emission spectrum and solar cell response.
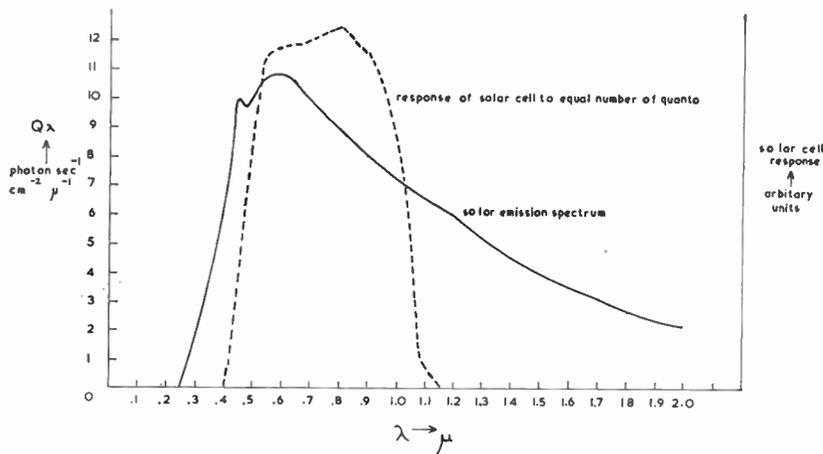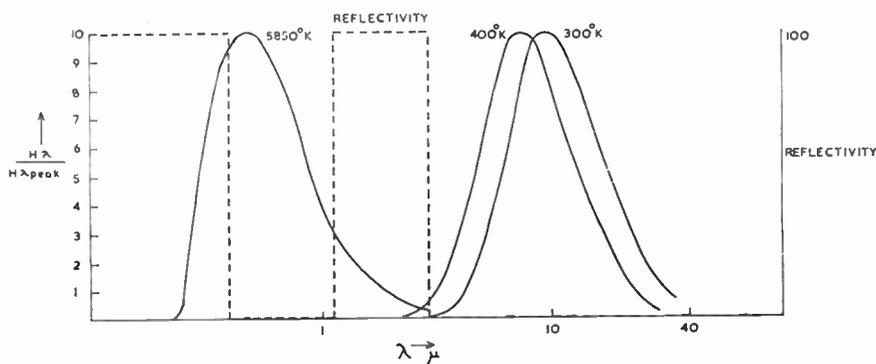
Fig. 8. Wavelength dependence of the reflectivity of an ideal solar cell assembly and the black body emission spectra for various temperatures.

a large fraction of that inside) can only produce heat if absorbed: it forms 33 % of the total energy available from the sun.

It has been shown above that untreated silicon cells may reach maximum temperatures of about 100° C, and in order to achieve efficient emission of this internally generated heat the emissivity should be large for wavelengths in the range 5–10 μm. As a result of the above considerations we can say that the reflectivity of an ideal solar cell assembly should vary with wavelength as shown in Fig. 8; emissivity is equal to the absorptivity which again is equal to (1 − the reflectivity for a perfectly absorbing body). The black body emissions corresponding to approximate temperatures of the sun and solar cell assembly are shown in Fig. 8.

In solar cell assemblies described to date the practice has been to use a glass window, with ultra-violet rejection filter, bonded to the silicon surface with a resin, the purpose of the u.v. filter being to avoid the darkening of the resin that can be caused by prolonged exposure to ultra-violet radiation.[3] Since suitable glass is opaque beyond 4 μm and has a fairly low reflection coefficient, it does serve as a fairly good emissive surface in the 5–10 μm regions, as well as giving the essential protection to the silicon from high energy electrons. Simple interference filters can be produced chemically or by evaporation to reduce the reflectivity in the region of peak sensitivity. The use of multiple evaporated films can of course further improve the optical properties of the system[4] and it will ultimately no doubt be economics that will decide

whether this more sophisticated approach is worth-while.

6. Conclusions

As the power supply is likely to be quite a large fraction (in weight and cost) of any unmanned space vehicle, it has been intended in the above discussion to show how the choice of orbit and orientation stabilization etc. have a profound effect on the performance of a solar cell assembly. This is accentuated by the damage done to solar cells by the high energy proton flux in the Van Allen belt, against which there does not seem to be any suitable protection.

7. Acknowledgments

The authors wish to thank the Plessey Co. Ltd. for permission to publish this paper and Dr. H. Crystal, Mr. I. Corby, Mr. K. Noble and Mr. A. Richardson, of these laboratories for the supply of solar cells.

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Twenty-Five Years of Television

The first regular public "high-definition" television service in the world was started by the British Broadcasting Corporation on 2nd November 1936 from Alexandra Palace, London. The Silver Jubilee has been marked in numerous ways, most notably by a Banquet in the Grocer's Hall in the City of London on 7th November, at which the Prime Minister was Guest of Honour and paid tribute to the B.B.C.'s high level of achievement in programme content and in engineering. The President of the Institution was represented at the Banquet by Mr. Leslie H. Bedford, C.B.E., a Vice-President and Past President, who was himself responsible for numerous advances in receiver design.

By commencing this service—confined at first to the London area—the B.B.C. initiated the building of major industries in the manufacture of equipment and in the production of programmes, which have made a considerable impact on the lives of millions of people all over the world.

Mechanical v. Electronic Scanning

In 1936 the present standard of 405 lines 50 fields interlaced was established as a result of the famous series of comparative tests between the Baird mechanical scanning system and the Marconi-E.M.I. electronic system. The rival Companies installed their vision equipment at Alexandra Palace, the chosen site of the London Station, a common sound transmitter and a common aerial system, both manufactured by Marconi's, being used.

The Baird employed 240-lines scanning with 25 pictures per second, the scanning process being carried out by Nipkow discs running at 6000 rev/min in a vacuum. Spotlight scanning was used for head-and-shoulders work, but for general scenes an indirect system was employed, which consisted of an intermediate film scanner which filmed the scene and developed, washed and fixed the pictures within 30 seconds, whereupon they were scanned for transmission.

The Marconi-E.M.I. system operated on 405 lines with all-electronic interlaced scanning, using Emitron cameras as the picture source. Although the picture rate was nominally 25 per second, the interlacing provided an effective repetition rate of 50 per second, with a marked reduction in flicker.

When the station was formally opened, Baird's and Marconi-E.M.I. operated their equipments on alternate weeks. The few receivers on offer at the time incorporated cathode ray display tubes and had a switch to change over from one line standard to the other. On 5th February 1937 the Postmaster-General announced that henceforth only one system would handle the transmissions—the Marconi-E.M.I. Baird had paid the penalty for his adherence to mechanical scanning.

Ironically, whilst the name of John Logie Baird is familiar to all, the names of Shoenberg, Blumlein, N. E. Davis, Franklin and others of the brilliant team who gave us television as we know it today are virtually unknown outside engineering circles—doubtless because they worked in secret as a team on a system which derived nothing from that used by Baird.

Just before the anniversary, the first volume of a definitive history of British broadcasting—"The Birth of Broadcasting" by Professor Asa Briggs*—was published, dealing with the early days of sound broadcasting, and subsequent volumes will no doubt provide an equally fascinating account of the beginnings of the television service.

Expansion of the Service

With the decision on systems made, the B.B.C. went ahead steadily with the new service. A particularly notable landmark before the war was the first outside broadcast —the Coronation procession of H.M. King George VI in May 1937—but the close-down on 1st September 1939 held up all further development until the London service restarted on 1st June 1946 (using for the next ten years, until the opening of the new station at Crystal Palace, the *same transmitter* and aerials as before the war!).

Over the past fifteen years, the B.B.C. has built up its nation-wide coverage, with five high power stations, seven medium and eleven low power satellites, the latter to be increased during the next four years by a further 25, giving coverage of 99·4% of the population—higher than in any other country in the world. Studio centres have been built in London, and regional centres have also been set up. Eurovision has added the television services of Europe to the potential programme sources.

The Question of More Lines

Because of the penalty which so often attends pioneering efforts, British television has, in the view of many, been hampered by its decision to continue with the 405 line standard. Three years after the British service started, American television began in New York (on 30th April 1939) using a standard of 441 lines 60 fields, subsequently increased to the present 525 lines. Advocacy of increasing British definition standards to a comparable figure (supported incidentally in a contemporary Institution report†), was renewed after the six-year suspension of the service due to the war, but the decision was taken to continue the original standards. There has indeed been fair agreement that comparisons of the quality of the British 405 line picture with the 625 line picture used in Western Europe have not shown the poorer definition which might have been expected on the former system—a tribute to the engineering standards maintained by the B.B.C. at the transmitter, the G.P.O. in its links, and the receiver manufacturer.

In the last few years, however, the desirability of a change to 625 lines has been put forward for a number of reasons, some of which are referred to in the Institution's survey‡ prepared earlier this year for consideration by the Committee on Broadcasting. The future of British television—which since 1955 has included the rapidly growing commercial television network operated by the Independent Television Authority—will largely depend on the Government's final decisions on the recommendations to be made by the Committee on Broadcasting.

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* Published by the Oxford University Press.
† " Post war development report—Part 1," *J.Brit.I.R.E.*, 4, p. 138, October–December 1944.
‡ " Radio and television broadcasting in Great Britain," *J.Brit.I.R.E.* 21, pp. 379–87, May 1961.

Radio Engineering Overseas . . .

CONTACT WETTING

Surfaces with a high resistance may form during the practical operation of audio frequency circuit contacts. In order to avoid signal fading, i.e. a reduction of the speech level, various wetting methods have been proposed in addition to the generally used d.c. wetting and have been tested with various degrees of success. The characteristics properties of the various wetting methods, i.e. d.c., intermittent, high frequency and pulse, are discussed in a German paper and for the purpose of comparison, recommended values are derived for fading, unbalance loss and noise voltages.

"The various methods of contact wetting and the basis for a critical examination", L. Borchert and K. L. Rau. *Nachrichtentechnische Zeitschrift*, **14**, No. 11, pp. 555–9, November 1961.

DIELECTRIC-LINED CIRCULAR WAVEGUIDES

Circular waveguides with dielectric wall lining offer advantages for the transmission of the H_{01} mode and variations in the thickness of the lining cannot be completely avoided in making such dielectric layers. The disturbances due to such irregularities have been analysed by a German engineer and the results compared with measurement values. It turns out that the conversion of the H_{01}-mode into parasitic modes is proportional to the square of frequency and to the third power of the thickness of the dielectric layer. With a superimposition of the conversion products due to geometrical irregularities of the waveguide and the dielectric lining a partial compensation of the overall disturbance can occur.

"Determination of the mode-changes in circuit waveguides with irregular dielectric lining", W. Janssen. *Archiv der Elektrischen Übertragung*, **15**, No. 11, pp. 525–536, November 1961.

TUNNEL DIODE U.H.F. AMPLIFIER

A recent German paper investigates the signal and noise behaviour of an amplifier cascade that consists of a tunnel diode type straight amplifier as a prestage, followed by a conventional triode amplifier. Transducer gain insertion gain, and bandwidth of the tunnel diode type straight amplifier are calculated as well as the minimum overall noise figure that can be attained, if no secondary condition exists, or if the bandwidth of the prestage is prescribed and the conditions for a low-noise tunnel diode are derived. Measuring results are given, as found on an experimental set-up for frequencies of 500 Mc/s and 600 Mc/s which are in fair agreement with theoretical investigation. With an insertion gain of 10 dB the prestage exhibits a relative bandwidth of 5%. At 500 Mc/s and a relative bandwidth of 1% the minimum excess noise figure of the cascade amounts to 2·5. With respect to the minimum excess noise figure of the conventional triode post-amplifier this means a reduction by a numerical factor of approximately 2.

"The tunnel diode straight amplifier with low-noise prestage for the u.h.f. band", H. Rieck and R. Maurer. *Archiv der Elektrischen Übertragung*, **15**, No. 11, pp. 495–507, November 1961.

MAGNETIC AMPLIFIERS USING TRANSISTORS

Self balancing type magnetic amplifier circuits using transistors with negative feedback windings in the base drive circuits, are described in a recent Japanese paper. While the gate circuit is the same as for the conventional magnetic amplifier circuit, the control windings are connected to the transistor circuit. Input signal voltage, supplied to the base circuit of transistors, controls the collector current of transistor, changing the flux of magnetic cores. Induced voltage fed to the base circuit through the negative feedback windings is compared with the input signal voltage, and the driving transistor is activated by the difference of these quantities. The voltage gain of this amplifier is not affected by the magnetic core characteristics and transistor constants and since there is no interaction between cores, the amplifiers have inherently half cycle response.

"Self balancing type magnetic amplifier using transistors", F. Hamaoka and E. Yamazaki. *Mitsubishi Denki Laboratory Reports*, **2**, No. 4, pp. 357–378, October 1961.

RATE COUNTER

The rate counter described in a German paper is used for determining the statistical distribution of fading periods or, in general, of periods during which a given level is exceeded or not reached with irregular fluctuations within the range from 0·2 ms to 132 seconds. The values of a measured group, which may have any duration within these limits, are quantized by a 20 step time grading. A counting device with 20 counting channels corresponding to this grading permits the determination of rate of occurrence as a function of the duration of the measured events. A few examples are given of measurements of fluctuations in telegraphy distortions and of the fading duration as well as the fading frequency on h.f. links and also of measurements of the pulse duration distribution on facsimile links.

"A rate counter for statistical time measurements", G. Heinzelmann, B. Lenhart and K. Vogt. *Nachrichtentechnische Zeitschrift*, **14**, No. 11, pp. 529–36, November 1961.

THE AUSTRALIAN DME SYSTEM

A series of papers has recently been published in the *Proceedings of the I.R.E. Australia* describing the Australian distance measuring equipment. In the first paper, the role of DME in an air traffic control system is summarized. The concept of positive control, the changes in the nature of the traffic and the influence of these developments on the Australian DME system are then discussed.

Operational requirements make it necessary for DME beacons to provide gapless coverage for a distance of 200 miles and altitudes up to 50 000 ft. Propagation theory and experimental results given in the second paper show that the coverage is limited by the deep minima caused by the ground-reflected signal. This is a function of the effective antenna height and of the terrain near the beacon. Since the siting of a beacon is usually dictated by operational considerations the effect of the minima can only be overcome by decreasing the height of the antenna (where possible) or by the fitting of a high gain receiver.

An improved airborne set for the Australian 200 Mc/s DME system using all solid state devices (apart from two valves in the transmitter) is then described. Considerable reductions in size, weight, and power consumption have been achieved, together with improved performance and reliability. A major improvement has resulted from the use of the Tacan coarse-fine system of range measurement. A high accuracy ($\pm$ 1%) time delay circuit and a new method of automatic tracking suitable for transistors are basic elements in the unit. The 224 Mc/s receiver includes a crystal controlled local oscillator and a gated a.g.c. circuit. $p–n–p–n$ devices replace thyratrons as high power switches in the modulator.

The next paper describes a new transistorized pulse selector; this decodes the 48 pulse-duration/pulse-separation codes and generates a response to the selected code. The techniques which provide precise timing are discussed.

A brief outline is given in the fifth paper of a 224 Mc/s airborne receiver, emphasis being then laid on the novel 30 Mc/s i.f. amplifier; this consists of a multi-section band-pass filter followed by a six-stage broadband amplifier. The advantages of this approach are discussed.

Finally the development of a production prototype transistorized DME set is described. The design not only provides an equipment of light weight and low power consumption but a considerable improvement in precision, reliability and maintenance requirements has been achieved when compared with the existing set. Some of the techniques used are described in detail.

"DME and air traffic control", E. Stern (pp. 541–5).
"The effects of terrain coverage gaps in the Australian 200 Mc/s DME system", D. L. Ball (pp. 546–51).
"An experimental transistor DME airborne set", R. D. Ryan, F. R. Hall and F. G. Tonking (pp. 552–63).
"A forty-eight channel pulse selector for the Australian DME system", P. W. Headford (pp. 564–9).
"A transistorized airborne receiver for the Australian DME", J. Ward (pp. 570–6).
"Development of a commercial transistorized DME set for airborne use", F. R. Hall and B. R. Johnson (pp. 577–89).
Proceedings of the Institution of Radio Engineers Australia, **22**, No. 9, September 1961.

RADAR INFORMATION

It is very difficult, if not impossible, to construct in practice a perfect radar receiver. Two French engineers have shown that this difficulty can be lessened by first converting the untreated video from a radar installation to normalized video (with a signal "0" or "1" of fixed duration, repeated by reference to a timing mechanism), then storing this binary information. The proper treatment of information so stored makes it possible to produce a receiver whose sensitivity is only 1·8 dB below that of a perfect receiver. The exact position of the different plots can be determined by the conventional treatment of the sequence corresponding to "0" and "1" signals. Two kinds of methods are used for examining the output; the weighting of the apparent maximum or averaging between the commencing and final outputs of the scan. A receiver of this type has been built for the purpose of discovering experimentally the performance which can be expected. This receiver uses a magnetic drum store.

"Automatic extraction of radar informations in numerical form", L. Gerardin and R. Barbier. *Onde Electrique*, **41**, pp. 783–94, October 1961.

REMOTE RADAR PRESENTATION

A paper by Canadian engineers describes how video signals from an air traffic control radar can be converted into a signal of less than 1·5 kc/s bandwidth in a dual-gun storage tube. By modulation on an audio carrier, the signal is transmitted through a telephone circuit of facsimile transmission quality. At the receiving end, the signal is detected and written into another storage tube. Television read-out is used to display the results on television monitors.

An associated paper describes an equipment whereby television type alpha-numeric symbols are generated for simultaneous display with converted radar information. Traffic controllers can easily select and position the symbols on monitor screens.

"Slowed down video permits transmission of radar pictures over telephone lines", T. W. R. East and M. M. Feilchenfeld, and "Symbol generator helps air traffic controllers identify and direct aircraft", R. W. Dankwardt. *Canadian Electronics Engineering*, **5**, No. 11, pp. 36–40, November 1961.

MEASURING AIRCRAFT SPEED AND POSITION

It is shown in a recent Czech paper how the interference of the directly received beam reflected from the moving target (e.g. an aircraft) can be exploited for determining the flight parameters. Assuming linear course and constant speed within a short time interval the relations for calculating speed and distance from the point of reception are stated. Furthermore the influence of frequency modulation on the nature of the interference as well as some specific problems of v.h.f. waves propagation are evaluated.

"Determining the speed and position parameters of airplanes by means of interference of v.h.f. long distance reception", J. Pokorny. *Slaboproudy Obzor*, **6**, No. 8, pp. 487–91, August 1961.

SUBJECT INDEX

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INDEX OF ABSTRACTS

This index classifies under subject headings the abstracts published through the volume in "Radio Engineering Overseas" and reports of papers read before Local Sections.

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Archiv der Elektrischen Ubertragung (Germany)

Canadian Electronics Engineering

Engineering Journal of Canada

Indian Journal of Physics

L'Onde Electrique (France)

Mitsubishi Denki Laboratory Reports (Japan)

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