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FOREWORD

This special edition of the *Journal,* dedicated to undersea cable systems, is intended to mark in particular the very significant changes and contributions brought about by optical-fibre technology in terms of project planning, system design and system support. Planners are no longer constrained to the simple point-to-point systems of the coaxial era, because optical-fibre cables now offer considerable flexibility and complex configuration options; for example, plans recently announced for a further transatlantic optical-fibre system, TAT-9, include five landing points— Canada and the USA in the West, and the UK, France and Spain in the East — providing communication between any East-West combination as well as between the UK and Spain.

The transition from analogue coaxial cable to digital optical-fibre systems has required a new technology to be established and complementary technologies to be developed for the design, evaluation and operational support of these new systems. The common design parameter throughout is reliability, for not only must the overall design satisfy the reliability objective, but the component parts must be shown to exhibit the necessary low level of failure for this to be achieved. New acceleration mechanisms and correlation factors have had to be established for this purpose.

Most of the work that has made undersea optical-fibre cables a reality has taken place in only the last five years and much more is promised — new glasses, lasers, modulation techniques etc — which indicates that this new technology will continue to meet the needs for undersea communication systems for many years to come.

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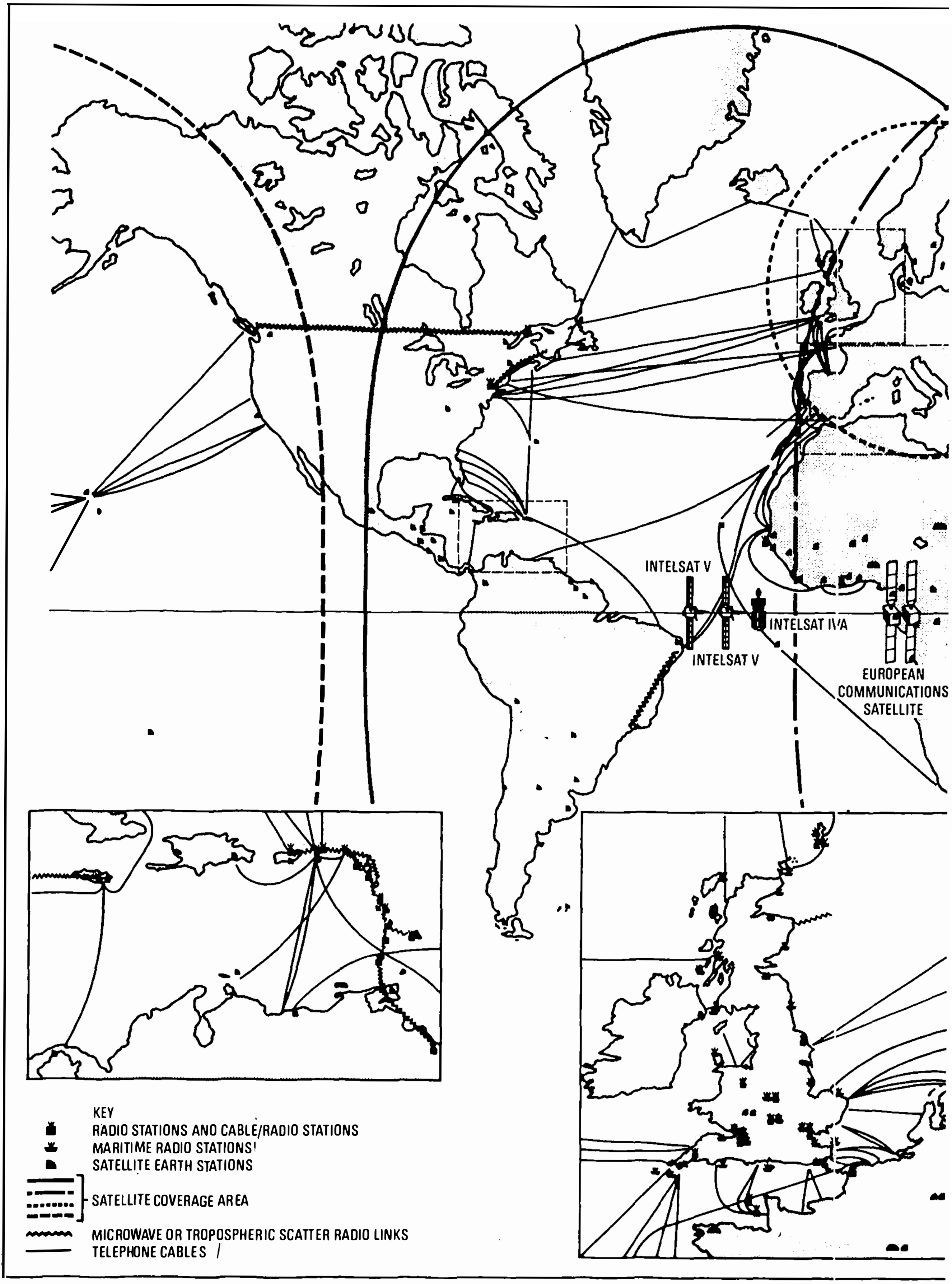
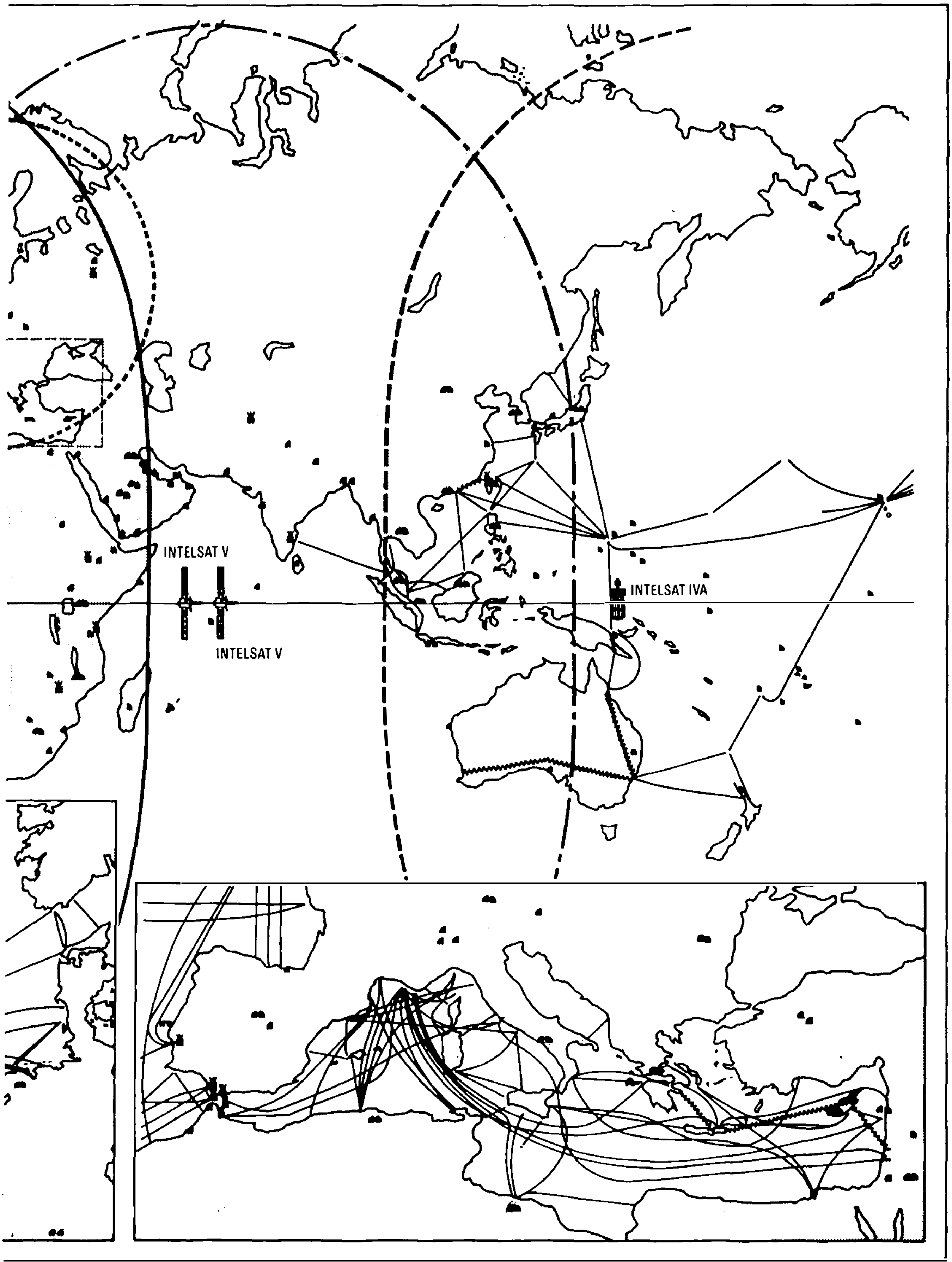
The International Telecommunications Network

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The International Transmission Network and the Role of Submarine Cable Systems

D. BALL, C.ENG., M.I.E.E., M.I.E.R.E.†

UDC 621.315.28 : 621.395.74

As an introduction to the technical articles on optical-fibre submarine cable systems which follow, this article considers the components of the international transmission network, summarises regional developments, gives factors which are taken into account in the development of the network, and indicates the role played by submarine cable systems in network development.

INTRODUCTION

The international transmission network (ITN) is the world-wide dynamic and ever-developing means by which international communication services are relayed between countries and continents. Its purpose is to provide the means by which customers of British Telecom International (BTI) and its overseas partners can communicate quickly, reliably and in a cost-effective manner. The individual components of the ITN are satellite links, submarine cable systems, microwave radio-relay links, and the national networks of countries through which international services are routed or in which they terminate. Both high-frequency (HF) radio and tropospheric-scatter links are also in use, but to a relatively insignificant extent at the present time.

HISTORICAL DEVELOPMENT OF THE INTERNATIONAL NETWORK

The first means of international communications was by a submarine telegraph cable. The first successful transatlantic telegraph cable was laid in 1858 and throughout the late-1880s and early-1890s a world-wide telegraph network was developed. Some submarine telephone cable systems were also laid over short distances during this period, but all these early systems were of stranded copper wire and provided very limited capacity. For example, the early UK–France cables had a capacity of only two circuits.

In the early-1890s, radio telegraphy was introduced to supplement the cable network. Radio telephony was introduced in the late-1920s and from this time, up to the late-1950s, HF radio transmissions provided the backbone of the global telecommunications network; indeed, a small number of HF radio routes, telephone and telegraph, are still in service today.

During this period, the development of submarine cables continued; significant developments included:

(*a*) higher capacity coaxial systems during the 1930s (for example, the 12-circuit UK–Netherlands cable in 1937);

(*b*) the first repeatered cable system between Wales and the Isle of Man (48 circuits) in 1943;

(*c*) the first deep-water cable system between the USA and Cuba (24 circuits) in 1950;

(*d*) the first transatlantic twin cable-system, designated *TAT 1*, providing initially 36 circuits between the UK and the USA in 1956; and

(*e*) the first single cable system, using lightweight cable, designated *CANTAT 1*, providing 60 circuits between the UK and Canada in 1961.

By the mid-1960s, over 70 international submarine cable systems were in operation, including systems in the North Sea, English Channel, North Atlantic, Mediterranean, Caribbean and the Pacific. These systems provided a comprehensive range of high-quality international links.

In 1965, the first commercial communications satellite, EARLYBIRD, was brought into service over the Atlantic Ocean, providing 240 circuits. The INTELSAT‡ system has expanded rapidly since its inauguration and there are now seven INTELSAT satellites in operational use over the Atlantic Ocean, three over the Indian Ocean and three over the Pacific Ocean, providing international links between more than 100 countries.

The complementary nature of submarine cable systems and satellites for intercontinental communications is well established and each has particular advantages that can be utilised in particular circumstances to enhance the network. The multi-destination capability of satellites has an inherent flexibility which is of particular value when linking a number of countries, some of which may be inaccessible by other means, without transiting intermediate countries.

The relatively limited life of satellites, presently 5–7 years although now being extended, enables advantage to be taken of new technological developments. A submarine cable system has a design life of 25 years and, indeed, some early valve-operated repeatered systems are still in service. A particular advantage of the submarine cable, however, is the relatively small overall transmission time delay compared with satellites: 30 ms on, for example, the transatlantic cable route compared with 250 ms for geostationary satellites. This factor is particularly important when transit switching, data transmission systems and the establishment of routes to countries which use a domestic satellite distribution system are considered. Two satellite links in tandem represent an unacceptable delay.

The development of satellites and submarine cable systems has continued side by side since the early-1960s, and there are now nearly 200 international cable systems in service. The development of submarine cable networks has tended, not unexpectedly, to take place within well defined geographical limits, submarine cables being essentially regarded as facilities for providing point-to-point links independently of similar developments in other regions. Such developments of regional cable networks can be seen in a number of areas, for example, the North Atlantic, Pacific, Mediterranean basin and the North Sea.

The world-wide telecommunications network to which BTI's customers and those of its overseas partners have access is shown on the map on p. 70. It can be seen that in the North Atlantic, cables provide direct links between three European countries (UK, France and Spain) and two North American countries (USA and Canada). In the Pacific area, demand for circuits is lower than in the North Atlantic, and considerable distances are involved. This leads to the provision of cable systems in several segments, partly for technical reasons, but also to give the potential for utilisation of a larger number of traffic streams. The Mediterranean and North Sea represent regions of high circuit density

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† Satellite and Lines Executive, British Telecom International

‡ INTELSAT—International Telecommunications Satellite Consortium

within comparatively small areas. In these circumstances, submarine cables provide the most economic solution, and complex networks have developed with many direct links being provided to meet growing demand.

BTI has played a prominent role in the development of submarine cable routes and, of the systems presently in operation, 29 terminate in the UK; BTI has an interest in a further 35 systems.

DEVELOPING NETWORK PLANS

The ITN can only develop by agreement between overseas partners, and the realisation of a particular international route is the result of the reconciliation of the desires and aspirations of individual countries with a disparate range of needs, organisation, awareness and cultures.

When planning the development of its international routes, each entity generates plans to accord with its own financial and service objectives. A prime objective is to provide customers with a good quality of service at all times at reasonable cost. To achieve this objective requires detailed consideration of a number of inter-related factors. The main elements include:

(*a*) the range of services to be provided and the forecast circuit demand;
(*b*) protection of service; and
(*c*) financial considerations.

These aspects are considered in more detail below.

Demand for Services

The range of international services which customers may wish to use or expect to be provided now and in the future include switched telephone and Telex services, customer leased services, data services, facsimile services, confravision and television links. Additionally, there is a need to plan for capacity for new services as yet unidentified.

The prime requirement of the network is to meet the forecast demand for all types of service at the desired grade of service. Circuit forecasts for a period of five years are agreed between overseas partners at regular intervals (usually annually) on a bilateral basis. For the purposes of planning international transmission facilities, forecasts for up to 15 years ahead are necessary. For traditional services, forecasting techniques fall into two categories: time series or trend forecasting based on simple regression techniques, and the more complex method involving mathematical and econometric models.

However, with the advent of new services and, in particular, the rising demand for high-speed data services, traditional methods of forecasting are tending to be of less value than in the past. The determination of forecast demand in, say, five or ten years time becomes a mixture of the application of market-research techniques and experience-based judgement. The latter assumes a growing significance as the need to forecast future demand at the year 2000 becomes evident for, say, the introduction of a new cable link or generation of satellites.

Service Protection

Elements of service protection include redundancy, media and route diversity, restoration and repair services.

The protection of the transmission links in the international network is of vital importance and is an integral part of planned network development. The ITN is configured so that for switched services, on the occurrence of link failure, the immediate loss of capacity does not reduce the quality of service on the route concerned below a specific grade of service, or introduce unacceptable levels of congestion at gateway exchanges as a result of customers' repeat call attempts. Arrangements are made so that within minutes, service is restored at or near to its normal level.

Redundancy

The prime form of protection against technical failure is the provision of duplicate, or redundant, equipment which is brought into operation automatically in the event of the partial failure of the system and allows normal service to continue uninterrupted. Redundancy is employed on the transmission elements of national networks and, to a limited extent, on international transmission links.

Diversity

Diversity is required to reduce the immediate effects of a breakdown from the instant it occurs until restoration or repair has been effected. Diversity is required for public switched services and has a limited application to private leased circuits. The minimum requirement is for path diversity, but there are additional advantages to be gained from media diversity (for example, cable and satellite) with advantages arising from independent streams of technological development and organisational arrangements. Taking into account various factors, for example, route size, cost of alternative facilities, etc., it is possible to establish preferred levels of both path and media diversity for particular routes.

Restoration

Protection against long-duration outage of a transmission link is obtained by re-routing service via alternative links. Restoration Working Groups covering major regions of the world with representatives of interested entities in those regions developing and agreeing restoration plans. These groups have produced a Universal Restoration Manual containing basic guidelines and recommendations. Provisions for 100% restoration of working circuits in the largest transmission facility in a given network is desirable, but for service with some distant countries the cost can be disproportionate to the benefit derived. In other cases, no practical scheme can be devised which suits all the interrelationships involved. However, with the emphasis on quality, complex re-routings are devised in order to maintain service to the customer.

Repair Service

An important part of service protection is a rapid cable-repair service. A high proportion of international circuits is carried in submarine cable systems which are covered by repair agreements, typically the *Atlantic Cable Maintenance Agreement* and the *North Sea Cable Maintenance Agreement*. Other agreements exist world-wide (for example, in the Pacific, and the Mediterranean). Under the terms of these agreements, owners of cable repair ships are reimbursed for the cost of keeping their cable ships available in the event of cable failure.

Current restoration plans can, in the majority of circumstances, cater for concurrent faults in several cable systems. Nevertheless, rapid repair of submarine cables is vital, and in the assessment of service protection costs this is a factor in determining the number of ships needed to maintain an effective repair service. Considerable advances have been made in the protection of submarine cable systems by improved armouring and burial techniques. Even so, repair ships are still required to cater for cable faults which, although significantly reduced in number over the last few years, do still occur as a result of trawling and ships anchoring. Faults in repeaters are very infrequent.

Financial Considerations

The relative cost of alternative facilities is an important consideration in the development of the network. Where one particular transmission facility results in a heavy cost penalty, the network should be developed with the aim of reaching a suitable balance between the preferred diversity and security of service, and the costs involved.

For example, comparisons may be made between the cost of cable and satellite routings, routing via cable or alternative terrestrial routes, or between providing cables of differing capacities to determine the most economic solution which meets service requirements.

Entities adopt different costing methodologies and methods of depreciation which reflect, for example, differences in interest rates and discount rates. The break-even point between cable and satellite facilities will depend principally on cable length and system capacity, although cost methodology may also have an effect.

NEED FOR NEW TRANSMISSION FACILITIES

As a result of the foregoing considerations, the development of the routing plans and associated bilateral discussions should, in some cases, identify the need for a new transmission facility to allow the optimum network development. Reasons for initiating planning of a major new facility include:

(*a*) the provision of additional capacity to meet forecast demand,
(*b*) the provision of path or media diversity,
(*c*) the provision of a more economic means of meeting demand,
(*d*) the provision of a direct link where none exists, and
(*e*) the replacement of a transmission facility due to be retired.

CABLE SYSTEM PLANNING

With earlier cable systems, planning, provision and financing were carried out on a bilateral basis by terminal countries with other potential users being invited to lease capacity or purchase *Indefeasible Rights of Use* (IRU) in the system. As cable system development continued, larger capacity systems became available offering a lower cost per circuit, and it became apparent that there were advantages in encouraging as many entities as possible to participate in new cables to optimise system size. This offered the benefit of lower cost per circuit for all users and allowed smaller entities, with limited technical and financial resources, to become involved in major project planning. An early example of this approach was the provision of Pacific cables (for example, COMPAC, SEACOM) by the British Commonwealth Partnership during the 1960s. The principle of co-ownership is regularly adopted today with potential co-owners being involved in project planning from an early stage.

The planning of a new cable system falls broadly into phases as follows:

(*a*) Independent studies by individual entities, followed by discussions either bilaterally or within *ad hoc* planning fora to establish the possible need for a new system. These discussions result in agreement on the broad definition of the project and agreement in principle to proceed.

(*b*) A series of formal meetings of potential co-owners to define the project in detail and reach agreement on the key factors such as system size, landing points, timing, sharing of costs, method of procurement and project management.

Decisions on these items lead to the production of a specification, invitations for tender, and the development of a *Construction and Maintenance Agreement* (C and MA). This agreement includes a definition of the terms under which the co-owners participate in the system. The C and MA also leads to the establishment of a committee of co-owners to progress the detailed planning, manufacture and bringing into service of the cable. Sub-committees are also established to consider in more detail circuit assignment, routing and restoration, sea route selection by survey engineering, construction and commercial activities, and financial and administrative matters.

This committee structure replaces the meetings of potential co-owners which co-ordinated the second phase of planning. This approach to cable system planning has been adopted successfully in a number of regions in the North Atlantic (TAT 7 and TAT-8) South Atlantic (ATLANTIS) and the Pacific Ocean (ANZCAN). Planning arrangements for TAT-8 are detailed elsewhere in this issue of the *Journal*[1].

CONCLUSION

This edition of the *Journal* looks to the future and is largely devoted to developments in optical fibre submarine cable systems. However, the era of analogue submarine cables is not yet passed, and many such systems will remain part of the international transmission network up to and beyond the year 2000. Present studies are aimed at determining the optimum method of utilising analogue cable systems in the interconnection of essentially digital national networks. But with the progressive digitalisation of national networks stimulating the introduction of new services, it can be expected that complementary digital capacity in the international network will be provided to meet the growing demand for these services internationally.

Both cable and satellite will be available to meet demand, and the two media will continue in their complementary role.

TAT-8 will come into service in 1988, primarily to provide North American–European needs, but with a component of capacity linking Europe with countries beyond the USA by interconnection with the HAW 4/TPC 3 cable systems. These systems linking the USA mainland to Hawaii, Japan and Guam will be brought into service in 1988.

A second transatlantic optical-fibre cable system (TAT-9) is now being planned to be ready for service in 1991. This new system will link North America and Canada with three landings in Europe (UK, France and Spain) and will also incorporate a UK–Spain link.

Consideration is being given to further optical-fibre cable systems in the Pacific linking Canada with Australia, and a Europe–South Atlantic system is also being considered. In the North Sea, two optical fibre cable systems will have been provided by 1988: the UK–Belgium No. 5, installed in May 1986, and the UK–Denmark No. 4, to be installed in 1988.

INTELSAT already provides a highly-flexible global satellite coverage, and with the introduction of optical systems, submarine cables are developing in a much more integrated network sense with the use of submerged branching units, and the development of submerged multiplex equipment.

Another feature of optical cable systems is the potential to lay relatively-long systems without repeaters, thus simplifying system design and reducing costs due to the absence of repeaters, power-feeding and supervisory equipment.

The submarine cable system in its digital form will, in the future, play a role just as significant as, or more significant than, its analogue counterpart plays at the present time.

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[1] SMITH, R. L., and WHITTINGTON, R. TAT-8: An Overview. *Br. Telecommun. Eng.*, July 1986 (this issue).

Biography

David Ball is now Head of Network Management in BTI's Satellites and Lines Executive responsible for the planning and implementation, operation and maintenance of the International Transmission Network.

Submarine Cable System User Requirements

R. T. WOODFINE, B.SC., C.ENG., M.I.E.E., M.I.E.R.E.†

UDC 621.315.28 : 621.391.63

The beginning of the digital optical-fibre communications era, together with the present business environment, has led to a reassessment of some of the more traditional telecommunications operator/user requirements for submarine cable systems. This article discusses, in general terms, several of the factors that are being considered within British Telecom and by other submarine cable system users worldwide, and the impact that optical-fibre systems have had on them. This article is based on a paper first published at the Suboptic 86 Conference, Versailles, France, February 1986.*

INTRODUCTION

Since the development of the first submarine cable system towards the end of the last century, this medium has been utilised to an increasing extent worldwide by telecommunications operators to enhance their national and international networks to meet traffic demands.

A synergy has existed between the expanding needs of operators and the development of systems with lower unit costs. This pressure towards lower costs has become increasingly focussed and many users are actively promoting technological developments to facilitate rapid provision of economic, flexible, high-capacity and reliable systems that will satisfy the telecommunications needs of customers in both private and public sectors.

This article examines the impact that the new digital fibre-optic technology has made on submarine cable user requirements in this environment. British Telecom (BT) has extensive experience as a major user of submarine cables and in many instances has been the motivator towards the setting of standards or trends. This experience stemmed initially from the world's first transoceanic submarine telegraph cable system, (which was installed between Ireland and Newfoundland in 1859) and has continued to the present day, when BT's network extends to include a major portion of systems worldwide, a position which BT intends to maintain. BT is therefore well placed to assess the need for and influence the various user requirements considered below.

CAPACITY REQUIREMENTS

The capacity of a new submarine cable must be carefully matched to future demand to ensure an economic fill rate for the system; it is necessary to calculate the range of system capacities which most nearly meets the most economic planning period for the system under consideration. With the advent of high-bit-rate multifibre optical systems, the users' choice of capacity has been greatly enlarged thereby facilitating this matching. However, the attractive low incremental cost per additional fibre pair has enhanced the danger of making premature investment which could prove to be redundant or which, in this period of rapid technological advancement, could be disadvantageous in some other way. A further significant factor that users need to consider when dimensioning their systems is the availability of digital circuit multiplication equipment (DCME). The first commercial optical-fibre submarine cable systems have been designed to operate at around 280 Mbit/s, providing approximately 4000 × 64 kbit/s basic circuits per fibre pair. However, future provisions on high-traffic-density routes might justify systems of greater capacity and next generation systems operating at about 0·5 Gbit/s could become desirable. Most routes will be adequately served by 140 Mbit/s and 280 Mbit/s systems, although lower capacities might find application on unrepeatered routes.

The only practical option available to the submarine cable user during the analogue coaxial-cable era has been point-to-point systems of pre-defined capacity. However, with the advent of digital optical-fibre technology, a multitude of system configuration options has now been conceived by the users to add to the versatility of the technology and help satisfy not just the more obvious technical and economic criteria, but those which also offer a much wider range of investment method options; for example, an overall average distribution of costs or cost apportionment on a segment-by-segment basis.

The TAT-8 (Atlantic Ocean) system and subsequently the HAW 4/TPC 3 (Pacific Ocean) systems were the first to utilise these networking possibilities through the incorporation of simple branching. Possible future options include system line rates consistent with terrestrial network developments, multiple terminal (broadcast) working, path switching, active (multiplexed) branching, and safe powering arrangements enabling network segments to be isolated for operation and repair conditions.

RELIABILITY AND LIFETIME

Systems have traditionally been provided for long lifetimes, usually twenty-five years, and designed and engineered to operate within well-defined performance limits over that period. Total reliability to enable the systems to continue to operate entirely fault free for such long periods would be prohibitive in both cost and time for component and material qualification testing and the degree of redundancy that would be necessary. Thus, users have traditionally made an allowance for a small number of equipment failures to be incorporated by the suppliers into their design calculations and reliability test programmes. This will of course continue to be the case for optical systems.

An area worthy of continual review is that of system lifetime. With the rapid progress of technology and the promise of even greater developments in the future, the balance of costs may become such as to make a reduction in the planned service life of a system economic and desirable. This would not have a very significant effect on reliability testing unless service lives were reduced dramatically.

SUPERVISORY REQUIREMENTS

As analogue submarine systems evolved, it became necessary to have some means of monitoring their performance. This

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* WOODFINE, R. T. Submarine Cable System User Requirements. Proc. Suboptic 86 Conf., Versailles, France, Feb. 1986, p.427.

was necessary both as a diagnostic tool to enable faults on a system to be pinpointed and as an early indicator of deterioration in repeater health, thus allowing expensive submerged plant repairs to be scheduled at minimum cost and disruption. Submerged repeater monitoring equipment (SRME), therefore, became an integral part of each generation of submarine system, but with experience significant simplifications in monitoring capabilities became acceptable, and expensive and complex dedicated SRME no longer became necessary.

Although a major leap forward has been made in the introduction of fibre-optic technology into submarine cable systems, the requirement for the close monitoring of submerged regenerators has meant a return to a dedicated and complex SRME.

The facilities now required are, for example:

In-service:	Interrogation of error counters at each repeater Laser health indications Received optical power measurement
Out-of-service:	Optical and electrical loop-back

Of these facilities, error-counter interrogation and loop-back can be regarded as fault location facilities whilst laser health and received optical power can be regarded as indicators of performance degradation which may or may not be service-affecting.

However, as optical-fibre technology develops and as confidence increases, the trend in SRME should once again be away from complexity and the inclusion of large quantities of diagnostic features, and towards simple facilities required for effective fault location.

MAINTENANCE

The ideal submarine cable system is one which requires no maintenance; reality, however, dictates that this ideal cannot be assumed mainly because of 'outside' interference, which is by far the major cause of failures. Consequently, the maintainability of a system is an important consideration in procurement in terms of procedures, training, costs etc.

Those submarine system failures which occur on submerged plant and require the services of a cable ship involve significant costs. Consequently, great emphasis must be placed upon assessing the ease and speed of the work necessary aboard ships.

The advent of new technology, whilst highly desirable, presents new problems in relation to spare plant. To reduce the burden of spare plant, users in certain areas have combined their resources by pooling their spare equipment, thus enabling an optimum amount of plant to be available for the repair of a number of systems. This policy proved most useful during the analogue era when there was only a limited variety of systems available, but with rapidly advancing technology and the possibility of an increased variety of systems, this practice will have limited application. The increasing proportional cost of spare plant in relation to the total cost of a system is therefore a matter for concern.

Nor will the number of spare repeaters be reduced pro rata with the reduction in the number included in a system: a 'safe minimum' will be needed. Furthermore, costs of this minimum are liable to be higher than the larger stocks of analogue repeaters because of the increased unit costs.

Merit is therefore seen in mechanisms that reduce the cost burden of spares, such as perhaps suppliers maintaining pools of spares on behalf of users worldwide. The sophistication of repair techniques is anyway sufficient to add impetus in this direction.

Additionally, greater care and an increased level of routine testing might be required with optical-fibre cable to ensure that it remains serviceable throughout the many tank-to-ship loadings it might experience during its life.

NOVEL APPLICATIONS

The advent of the optical-fibre technology in the field of submarine cable systems has enabled users to utilise various new configurations and techniques in order to develop a more effective network.

One of the more important of the technological advances is the availability of long unrepeatered systems, which, in addition, offer the possibility of subsequent capacity expansion merely by upgrading terminal station apparatus as and when traffic growth requires.

Other system types which could also come to the forefront in certain limited markets over the coming years, are composite cables and cost-reduced cables. A composite cable might combine both power and telecommunications, thus enabling services to remote locations to be supplied more economically. Cost-reduced cables designed only with sufficient strength for installation, but not recovery, have application in circumstances where the risk of damage is slight and the time to replace it (for example, in networks having extensive redundancy) acceptable.

CONCLUSION

Exploitation of this new technology is still in its infancy. Such is the range and scope of future possibilities that great care will be needed optimally to match technological development to user needs.

Biography

Roy Woodfine joined the Post Office in 1964 as a Trainee Technician Apprentice at Ongar Radio Station. He subsequently gained a place at The City University and graduated with an honours degree in Electrical and Electronic Engineering in 1972. He then spent several years planning the main transmission network for Scotland before joining the Submarine Cable Systems Division of British Telecom International (BTI), where he more recently headed the group responsible for planning. He is currently the BTI Offshore Hydrocarbons Manager concerned with services to the offshore industries.

Optical-Fibre Submarine Cable Systems—The Way Forward

J. M. HORNE, C.ENG., M.I.E.R.E., D.M.S.†

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This article provides a general outline of the factors that have led to the development of optical-fibre submarine cable systems and gives a summary of their characteristics and highlights particularly the alternative redundancy solutions offered by different suppliers in order to meet the high reliability and long lifetimes required for these types of systems.

INTRODUCTION

British Telecom (BT) has taken an ownership interest in all international optical-fibre submarine systems for which contracts have so far been placed and has indicated its support for further schemes which would serve to extend worldwide its ability to offer the benefits of this latest technology to its customers.

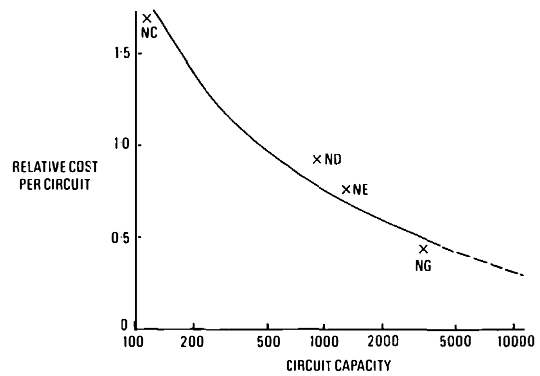
This edition of the *Journal* is devoted to a series of articles giving a detailed technological review of the facilities and the requirements for optical-fibre submarine cable systems; it also provides an outline of two of the systems, UK–Belgium No. 5 and TAT-8, which are currently being constructed, and are typical of those in which BT has an interest.

This article provides a general outline of the factors that have led to the development of optical-fibre submarine cable systems and gives a summary of their characteristics and highlights particularly the alternative redundancy solutions offered by different suppliers in order to meet the high reliability and long lifetimes required for these types of systems.

The article refers in part to the contents of a previous article[1] published in the *Journal*.

HISTORICAL REVIEW

Since the inception of submarine cables, systems have been designed and installed with increasing capacities commensurate with the increase in traffic. These systems based upon analogue coaxial technology have ranged from those provided in the early-1960s having a capacity of 120 circuits, to those currently available having a capacity of greater than 4000 circuits. This increase in system size has brought with it economies of scale, as illustrated in Fig. 1, which shows the resulting reductions in cost per circuit. Along with the benefits of reduced cost per circuit, however, have arisen some operational and reliability difficulties.



Note: NC, ND etc. refer to STC plc submarine system designations

Fig. 1—Reduction in cost per circuit

OPERATIONAL DIFFICULTIES

As system frequency bandwidths have been increased to provide the required capacity, so it has become necessary to utilise regions of higher attenuation in the cable. Coaxial cable of increased diameter and hence lower attenuation at the frequencies of interest has been provided in response to this situation and to maximise repeater spacing. There is, however, a limit to the diameter of cable that can be handled safely by the smaller cable repair ships, and this has now been reached with the current generation of coaxial cables.

These cables typically have a diameter of 37 mm (1·47 inch) and, when heavily armoured to given protection against trawls and anchors in shallow water, can have an overall diameter of 89 mm (3·52 inch).

RELIABILITY DIFFICULTIES

This increase in the diameter of the coaxial cable has not, however, totally compensated for the higher cable attenuation at the frequencies used, and repeater spacings have still been substantially reduced. This is shown in Fig. 2.

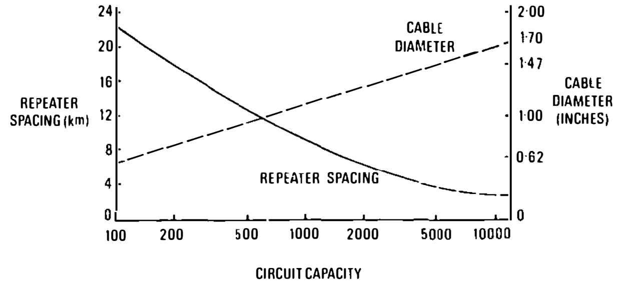


Fig. 2—Relationship between capacity, repeater spacing and cable diameter

A consequence of this decrease in repeater spacings is that, for a given route, more repeaters and hence more repeater electronic components are required. As these numbers increase, the reliability targets become more onerous to meet: currently these are set at no more than three ship repairs due to component failure during the system lifetime of 25 years.

LIMITED DEVELOPMENT POTENTIAL

By the 1970s, it became apparent that with these operational and reliability constraints, the further development potential

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† Satellite and Lines Executive, British Telecom International

of analogue coaxial systems was limited. It would not be possible with this technology to significantly increase system capacities and thus reduce cost per circuit to a level commensurate with need. Neither could analogue coaxial system technology provide the transparent digital media required to interconnect the fast growing national digital networks.

With these factors in mind, a search was started to find a replacement technology for use on submarine cable systems.

REPLACEMENT TECHNIQUES

To be acceptable, this replacement technology needed to provide the digital media required and a significant reduction in cost per circuit whilst retaining the reliability and maintainability of the existing range of analogue coaxial submarine systems. Within British Telecom International (BTI), several alternatives were considered, including both digital coaxial and optical-fibre systems.

Digital Coaxial Systems

The digital coaxial system, however, required the use of either two separate cables, or a single dual coaxial-cable structure. With the high line frequencies required, large-diameter cables would still be needed and regenerator spacings would be similar, or less than existing analogue systems. Therefore, similar operational and reliability constraints would exist.

Optical-Fibre Systems

Although at the time the study commenced the main development was for application in the terrestrial network for systems operating at the 0·85 μm wavelength using multimode fibre, it was apparent that the potential for optical-fibre systems to operate at the 1·3 or 1·5 μm wavelength over single-mode fibre would enable high-capacity economic submarine systems to be provided.

This development, combined with the networking capability[2] of such systems and their ability to provide a high-quality digital transmission path, with improved immunity to most of the problems of radio-frequency interference, made optical-fibre technology an obvious choice for future system applications.

Not surprisingly, these conclusions were reached by all the submarine system suppliers and major administrations operating such systems in the world and have led to the current situation where optical-fibre submarine systems are becoming commercially available.

DEVELOPMENT OF OPTICAL-FIBRE SYSTEMS

The considerable economic and operational advantages offered by optical-fibre submarine systems have led to an extremely rapid and concentrated development programme during the past five years. This is demonstrated by a recent estimate[3] which has put the world-wide cost of developing first-generation optical-fibre systems at between $440–500M. In that time, key components such as lasers, receivers, high-speed integrated circuits (ICs) and single-mode fibres have been moved from a laboratory to a production status, and regenerator designs capable of supporting 280 Mbit/s information rates have been realised.

Whilst this edition of the *Journal* contains articles describing both the development progress of key components, and system design and implementation, none documents the truly remarkable nature of this achievement relative to the previous approach to the development of submarine cable systems.

Such systems have always been extremely conservative in their application of new technologies in order to achieve high reliability. This usually meant that technologies were employed which had been used in terrestrial transmission systems for many years and had a proven reliability record. This can be seen from the fact that the first submerged repeater to use valves was installed in 1943, whilst the first to use transistors was installed in 1964, many years after these technologies were extensively used on terrestrial systems. The design of submerged repeaters has therefore always been evolutionary, with only those changes in technology essential to provide the required increased circuit capacity being employed.

THE OPTICAL-FIBRE REVOLUTION

With optical-fibre submarine cable systems, however, a revolution has occurred. For the first time, substantially new technologies are being deployed at the same time as they are being used on terrestrial systems; this requires a very extensive reliability programme and/or the incorporation of redundancy to achieve the required objectives for service life failure rates. With the high costs of provision and repair, the reliability requirement for optical-fibre submarine cable systems has necessarily been maintained as previously outlined.

REDUNDANCY SCHEMES

Each of the world's submarine system suppliers has initiated an extensive reliability programme covering the new components to be introduced in optical-fibre submarine systems. These programmes make full use of the acceleration factors that can be gained from high-temperature testing and, together with mechanical and environmental tests, attempt to determine failure mechanisms and the characteristic of life behavioural patterns.

Unfortunately, some components, such as lasers, are not susceptible to high-temperature acceleration testing as they cease to lase at temperatures much above 80°C.

There is also the problem of rogue failures. These failures, which are normally associated with some component weakness either in design or production, should normally happen only rarely. The actual level, however, would not become apparent until a large number of devices has been made and tested.

To cater for these situations and to reduce the extent of a component reliability demonstration in terms of the number of devices and length of testing time (both of which ultimately effect the system cost and commercial availability timescale), suppliers have incorporated redundancy schemes into their long-haul system designs. These schemes vary from supplier to supplier and extend from a relatively simple laser redundancy scheme to more complicated schemes involving both sectional and laser redundancy. The various schemes proposed are outlined below.

Laser Redundancy

The laser redundancy scheme requires one or more unpowered stand-by lasers to be provided for each regenerator (see Fig. 3). Laser change-over can either be automatic, being initiated when the threshold current of the working laser exceeds some preset limit or, more normally, be remotely controlled from the terminal station.

The input data stream can be switched from the working to stand-by laser by means of an electrical relay or by an electronic IC switch. The light output of the working and stand-by lasers can be coupled to the system fibre either by a passive coupler or by an optical-fibre switch. This switch can either be mechanical, physically moving the fibre, or static, in which case it changes the polarisation state of the fibre to achieve switching.

Fibre switches, especially those of the mechanical type, are more difficult to engineer reliably, but have advantages compared to a passive coupler in that their insertion loss is only 1–2 dB versus 3·5–4 dB for the latter.

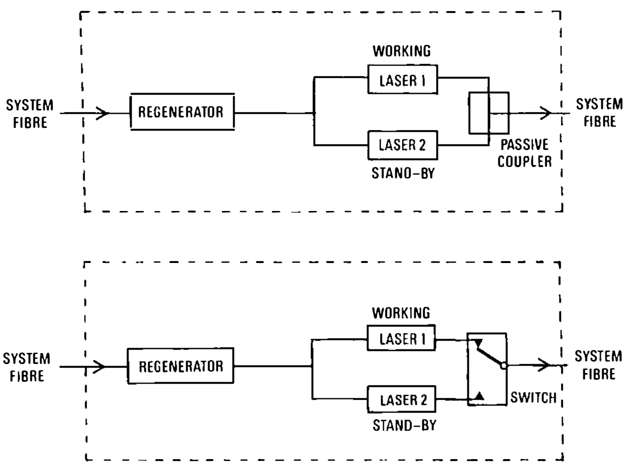

Fig. 3—Laser redundancy

Regenerator Redundancy

With regenerator redundancy, a working and unpowered stand-by regenerator is provided on each fibre path (see Fig. 4), normally in conjunction with laser redundancy. The switching from the working to stand-by regenerator is controlled remotely from the terminal and requires both an input optical-fibre switch capable of switching the system fibre to either regenerator path and an electronic IC switch to change-over the regenerator powering arrangements.

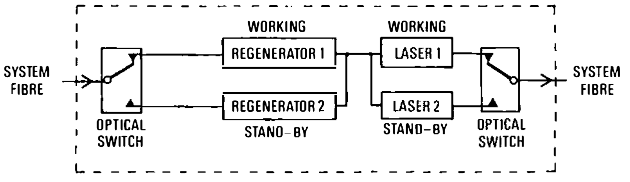

Fig. 4—Regenerator redundancy

Sectional Redundancy

In the sectional redundancy arrangement (see Fig. 5), a stand-by fibre path fully equipped with regenerators and capable of being switched into service on a section-by-section basis is provided for each direction of transmission. The switching of the elements of the stand-by path is remotely controlled from the terminal and the scheme requires either electrical relays or an electronic IC switch. As an additional element of security, laser redundancy can also be provided on both the working and stand-by regenerators.

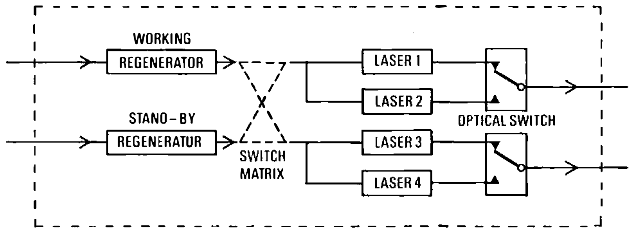

Fig. 5—Sectional redundancy

Future Redundancy Schemes

As more operational and lifetime information on optical-fibre submarine systems becomes available, it is expected that this will confirm the high reliability indicated by the component studies currently underway. With this additional confidence, it is possible that the level of redundancy required could be reduced, and so simplify and consequently reduce the cost of current technology.

Technology, however, does not stand still. Already the potential economic advantages of moving to the 1·5 μm wavelength are being seriously investigated as is the possibility of systems operating at higher (>0·5 Gbit/s) bit rates. Systems having these capabilities would require new components such as distributed feedback (DFB) lasers, GaInAsP avalanche photodiodes (APDs) and new families of ICs, together with new constructional technologies. It is therefore likely that redundancy schemes will be a necessary and continuing requirement for future-generation optical-fibre submarine systems in order to permit the exploitation of the latest technology at the earliest possible date.

INFORMED CUSTOMER STATUS

An interesting consequence of this drive to introduce the latest most economic technology is the increasing importance to BTI of maintaining its position as an informed customer. To this end, a considerable research and development programme continues in order to provide BT with sufficient expertise and support to be able to properly evaluate technological options, draw up equipment specifications and assess a supplier's offer.

The importance of this support arises from the increasing risk (or wider bounds of uncertainty on reliability information) that results from the use of new technologies for which only limited field experience is available.

In general, system suppliers are in a position to offer only two-year warranties against required system lifetimes of 25 years. The warranty offered is also normally limited to cover the replacement cost of the faulty hardware, and does not cover consequential costs such as the restoration of traffic during the failure which tends to be the dominant factor on a fully-loaded system. Both factors emphasise the need for the customer to be fully knowledgeable concerning the product.

CONCLUSIONS

This article has outlined the factors which have led to the choice of optical-fibre technology for submarine cable systems. The revolutionary way in which this has occurred and the different redundancy schemes that permit the early application of this technology have been outlined.

With the ever increasing pace of technological change, redundancy schemes are likely to become increasingly important as will the need to maintain BT's position as an informed customer.

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[2] HORNE, J. M. and FITCHEW, K. D. Network Planning: the new opportunities created by submarine optical fibre systems. Proc. Suboptic 86 Conf., Versailles, France, Feb. 1986, p. 333; and *Br. Telecommun. Eng.*, July 1986, (this issue).

[3] DAWIDZIUK, B. M Economic aspects of integrating novel technology into undersea telecommunication networks. Proc. Suboptic 86 Conf., Versailles, France, Feb. 1986, p. 317.

Biography

John Horne joined BT as a Technical Apprentice in 1964. He has been working in the field of submarine cable systems since 1969, and as Head of Systems Engineering Design Group with specific responsibilites for optical submarine cable systems within BTI since 1981. He obtained a Diploma in Management Studies at Middlesex Polytechnic in 1981.

The Loch Fyne Optical-Fibre Cable System

R. E. FERRIS and R. D. CHANNON†

UDC 621.315.28 : 621.391.63

This article describes the world's first trial of an optical-fibre submarine cable system, carried out in Loch Fyne. The article outlines the manufacture, installation and subsequent repair of the cable system and discusses the problems encountered. The experience gained during the trial has led to the new design of cable that is to be used in the UK–Belgium No. 5 and TAT-8 systems.

INTRODUCTION

In 1977, the Submarine Systems Division of STC commenced the design and development of an optical-fibre submarine cable. In 1978, British Telecom International (BTI) was approached by STC to participate in a trial system. The object of the trial was to gain operational experience of laying optical submarine cable and to monitor the long-term stability of the transmission characteristics of the optical fibres in a marine environment. This article outlines the manufacture, installation performance and subsequent repair of the trial system, from which essential experience and information were derived for the manufacture of production systems.

LOCATION

The first task was to identify a possible location for a long-term trial of a nominally 10 km length of cable. The criteria set for the location of the trial system were that as much of the cable as possible should be laid in water and that the water depth should be at least equivalent to that of the North Sea. The location finally selected was at Inveraray in Scotland, where there was an existing repeater station on the shore of Loch Shira/Loch Fyne. This loch, which had been formed by glacial action, was up to 150 m deep, although, in the location selected to lay the cable, the deepest water was just over 100 m with the majority of the cable lying in a depth of over 60 m. Fig. 1 shows a map of the location and the cable route.

TRIAL SYSTEM CONFIGURATION

Cable for the trial was made in 2 km lengths and jointed together in joint housings. Six fibres were packaged into the cable, four multimode and two single-mode.

The trial cable system comprised five nominally 2 km lengths of cable, giving an approximate overall length of 10 km, and was laid in a loop with both ends being installed into Inveraray repeater station. Fig. 2 shows a straight line diagram of the system, indicating the location of joint housings and a repeater, which housed a pair of 140 Mbit/s regenerators.

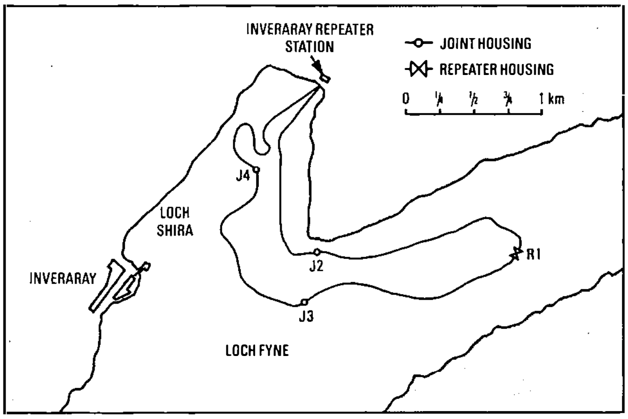
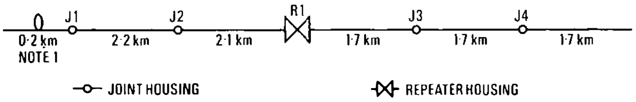


Fig. 1—Route of Loch Fyne optical-fibre cable trial



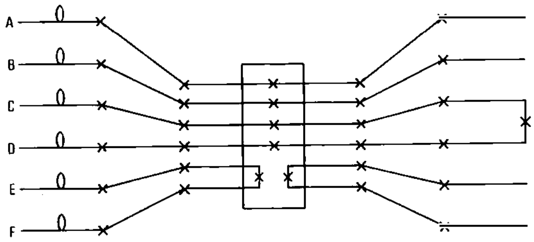
Note 1: 200 m reel of fibre jointed to each fibre in the cable

Fig. 2—Straight-line diagram of trial system

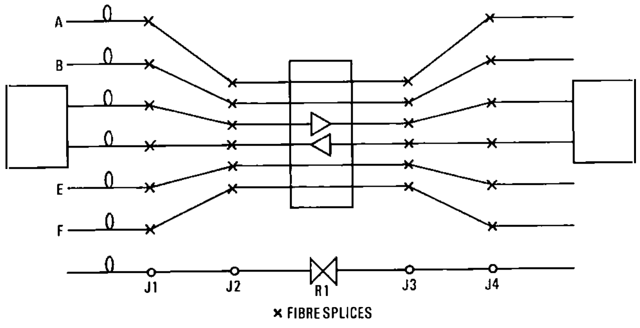
The system installation was implemented in two phases:

Phase 1 entailed BTI's cable ship *CS Iris* laying 10 km of cable with a repeater housing and associated cable terminations; the repeater was laid in the deepest water. During Phase 1, the fibres were spliced through the repeater housing, as shown in Fig. 3(*a*).

Phase 2, again carried out by *CS Iris*, involved recovering the repeater housing and inserting a pair of 140 Mbit/s regenerators, the fibres being configured as shown in Fig. 3(*b*). At the same time, terminal equipment was installed in the terminal station to provide a 139·264 Mbit/s interface. Most of the transmission tests were made at this interface, but muldex equipment was also provided to enable 4 kHz channels to be derived.



(*a*) Initial configuration



(*b*) Configuration after the installation of regenerators and terminal equipment

Fig. 3—Fibre configuration

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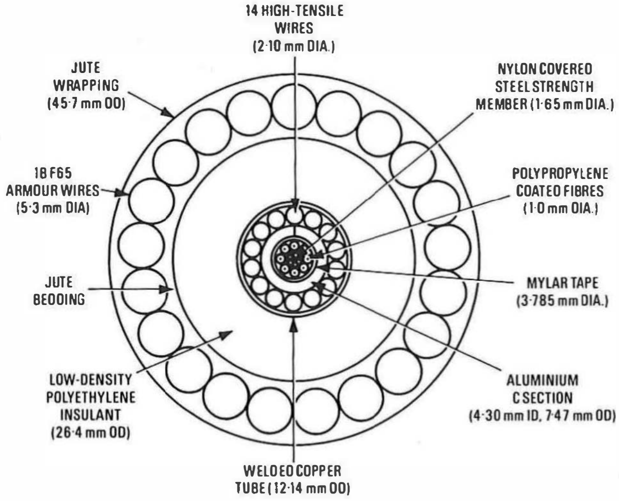
† Satellite and Lines Executive, British Telecom International

CABLE DESIGN

Fig. 4 shows a cross-section of the trial cable, and lists its characteristics. The fibres are housed in an aluminium tube that provides a hydrostatic-pressure-free environment. A layer of high-tensile-strength steel wires surround the aluminium tube. These steel wires are in turn surrounded by a copper tape, which is formed, seam welded and swaged down over the steel wires. Polyethylene insulation with a radial thickness of 7 mm is extruded over the copper tape. To provide external protection, a single layer of medium-tensile steel wires is applied over the cable.



Overall diameter	46·0 mm
Weight in air	46·6 kN/km
Weight in water	30·0 kN/km
Tensile strength	359 kN

Fig. 4—Loch Fyne cable cross-section and characteristics

The tensile strength of the cable was designed to ensure that, under adverse shipboard conditions experienced during laying and any subsequent repair operation, the maximum cable strain was less than 1%, and that any residual strain was minimised.

The tensile strength of the unarmoured version of the cable was 92 kN; this increased to 359 kN when it was armoured with eighteen 5·3 mm diameter medium-tensile steel wires. A load versus elongation characteristic of the armoured cable is shown in Fig. 5.

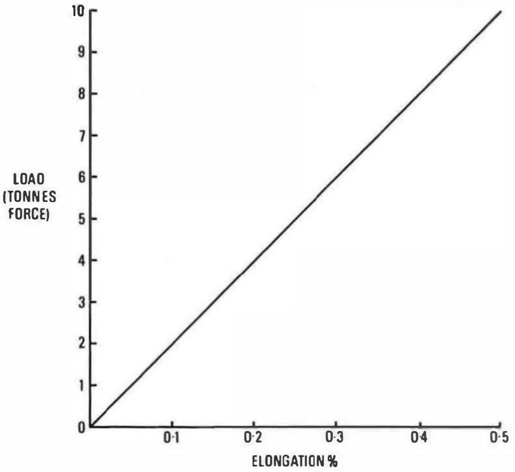


Fig. 5—Load versus elongation characteristic

The cable was manufactured in four stages:

Fabrication of the fibre package The fibres were helically laid around a central king wire and a helical binder tape wrapped around the package.

Fabrication of the composite power feed conductor The aluminium tube was formed around the fibre package and the high-tensile steel wires stranded around it. The copper tape was formed, welded and swaged down on the steel wires.

Insulation A polyethylene insulant was extruded over the copper tape.

Armouring Finally, the armour wires were applied to the cable.

During the fabrication stages, the temperature rise and elongation of the fibres had to be well controlled. The changes in elongation and fibre loss were measured using an optical method after each fabrication process. Fibre attenuation changes were negligible and the fibre strain increase was typically 0·15%; a large proportion of this increase occurred during the armouring stage and was due to the coiling of cable in the storage tanks. This strain was relieved when the cable was laid on the sea bed.

INSTALLATION

The first phase of the installation commenced in February 1980 with the installation of the cable and repeater housing by the BTI cable ship *CS Iris* (see Fig. 6). The fibre performance was monitored during the installation. As expected, most of the strain induced during the armouring/coiling operation was relieved, but strain of a similar magnitude was induced in the cable because of the laying tensions, and a net residual strain in the fibres of less than 0·1% resulted, with negligible change in fibre attenuation. The fibre insertion losses were measured at intervals prior to phase 2 of the installation.

Fig. 6—*CS Iris* on Loch Fyne

Phase 2 of the operation took place in May 1980, when the repeater housing was recovered and a pair of 140 Mbit/s regenerators inserted. These regenerators were spliced to two of the multimode fibres and the repeater relaid. Prior to this operation, terminal equipment was installed into the terminal station, and this allowed transmission measurements to be performed on the submerged regenerators. Fibre measurements were made prior to the recovery of the repeater and immediately after it was re-laid; these measurements have continued at periodic intervals up to the present day. Fig. 7 shows the insertion loss measurements made on the single-mode fibres at 1·3 μm. The figure shows that there is a trend towards increasing loss, which is more noticeable at the longer wavelength. In 1983, more detailed

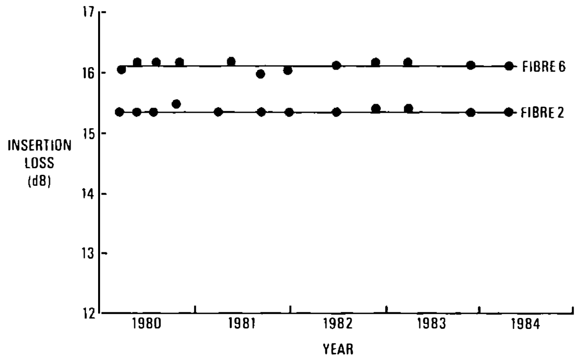


Fig. 7—Attenuation of single-mode optical fibres at $1 \cdot 3$ μm

analysis of the fibre losses at other wavelengths suggested that the presence of hydrogen in the cable was causing the fibre losses to increase.

HYDROGEN

The presence of hydrogen in analogue cables has been known for some time. This gas has caused only minor irritation during jointing operations, producing voids in the cable structure while injection moulding of the polyethylene dielectric was being carried out.

The need to monitor the long-term behaviour of optical fibres in sea water and hydrogen was first identified in 1980†. The confirmation in 1983 that hydrogen was being generated in the Loch Fyne system and having an adverse effect on the attenuation of optical fibre was a potentially serious problem for the designers of optical submarine cables. The optical-fibre trial cable loop in Loch Fyne assumed an unforeseen importance in the effort to quantify the hydrogen levels to be expected and the effect on fibres under realistic conditions.

The effect of hydrogen on fibres is to alter the attenuation characteristic of the fibre, and a number of attenuation peaks are produced at different wavelengths. The attenuation of the trial cable loop at these wavelengths dictated that only a few of these peaks could be investigated. Initial measurements at British Telecom Research Laboratories (BTRL) and Standard Telecommunications Laboratories (STL) on fibres in known concentrations of hydrogen established a relationship between the height of the hydrogen peaks and the hydrogen concentration. Once this relationship was known, a number of changes were introduced at Inveraray repeater station in an effort to establish the hydrogen levels within the cable structure.

Glands were fitted at each end of the cable to seal the individual fibres and power feed connections so that no gas could escape from the cable. The sealing glands included facilities for sampling the gas within the unblocked cable strand and connecting to a pressure transducer.

Initial spectral loss measurements and investigation of a hydrogen peak at $1 \cdot 240$ μm and the edge of a $1 \cdot 87$ μm hydrogen peak suggested a hydrogen concentration of about 5%. Since this level was deduced from an overall fibre loss measurement, it represented the average hydrogen concentration within the cable. Initial analysis of gas samples taken from the cable ends showed less than 1% of hydrogen. Successive samples drawn from the cable showed slightly increasing hydrogen levels further into the cable. At this time, it was thought that the hydrogen concentration gradient was an end effect, as the cable had only recently been sealed. The system was left for some months for the hydrogen to redistribute within the cable. Repeat measurements again showed hydrogen levels of about 1% rising slowly on successive samples. This result was confusing as it suggested that the hydrogen had not distributed evenly along the cable structure as expected. The fact that concentrations of 1% existed at the cable ends, whereas the fibre measurement suggested about 5% evenly distributed along the cable, implied that concentration of greater than 5% must exist elsewhere in the cable. Backscatter measurement at $1 \cdot 3$ μm, where the hydrogen effect is small, showed an even attenuation distribution without any noticeable tendency for loss concentrations where hydrogen levels might be high. Backscatter equipment operating at the hydrogen sensitive wavelengths was not available.

Mathematical modelling, carried out at BTRL and STL, of gas permeation within the cable structure suggested that the hydrogen generated at a point source in the cable would take a considerable time to permeate a few hundred metres from the point of generation. This mathematical gas model also showed that the permeation rate was very dependent on any manufacturing variation in the copper cladding of the centre conductor, the position and hydrogen permeation characteristics of any line joints. The position of line joints was known, but, as the cable was a prototype design not manufactured on fully engineered production equipment, the number and position of any manufacturing variations were in some doubt.

The possibility of completely evacuating and analysing the gas from the cable was considered, but this was overruled by a reluctance to invalidate any further experiments on the system until the problem had been completely identified. Routine measurement of the system continued while a number of options were considered.

In February 1985, during a routine visit to the station by BTI staff, a fault was located in the submarine cable. By using backscatter equipment developed at BTRL, breaks were located in both monomode fibres about half way between the terminal and the repeater. The two available multimode fibres showed attenuation anomalies at the same position. The two remaining fibres were permanently spliced to the terminal equipment and operating error-free through the submerged repeater. No electrical fault could be detected anywhere on the cable.

In conjunction with STC, it was decided to repair the system and recover the working repeater by using *CS Monarch*. This decision had a number of advantages because it provided first-hand operational experience of the testing, jointing, and repair techniques which had been developed for repairs to optical systems in the North Sea. It also allowed the working submerged repeater to be recovered for examination by STC, and gas samples to be taken from a number of points along the cable length.

REPAIR OPERATION

The repair commenced in July 1985. The two fibres connected to the terminal equipment were cut and backscatter measurements made on all six fibres. The fibre breaks on the single-mode fibres were reconfirmed, as were the attenuation anomalies on the multimode fibres. Disconnection of the terminal equipment allowed the remaining two fibres to be tested. This showed for the first time that, although the system was still working error free, attenuation anomalies were present in the same position on these remaining fibres.

The repair commenced with *CS Monarch* lifting the submerged repeater without cutting into the cable. In order to minimise the amount of gas leaking from the cable, the armour wires were cut and turned back without the cable core being damaged. Once the core had been cut, compression pipe fittings were screwed onto the copper conductor over the strand, and this enabled all the cable ends to be

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† Taylor, S. A. The Protection and Installation of Submarine Cable in Hazardous Deep Water Areas. IEE Conference on Submarine Telecommunication Systems. 26–29 Feb. 1980.

quickly sealed until samples were taken. A number of samples were taken in both directions at each cut into the cable; some samples were analysed on-board with a portable gas analyser, while other samples were returned to STL and BT for independent analysis.

Samples were taken from each side of the repeater as it was cut out of the system. On one side of the repeater, the hydrogen levels were 10%, while the other side, towards the fibre faults, had hydrogen levels of 20%. The good cable end was buoyed off, and recovery of approximately 2·5 km of cable towards the fault commenced. At the fault position, a small amount of damage was noted to the outer serving of the cable. A 125 m length of cable containing the faults in the fibres was cut out of the system and sealed to prevent the escape of any gas. Samples were taken from each side of the fault position; these showed hydrogen levels of 5% towards the repeater and 0·5% towards the terminal station. This confirmed a gradual decline in hydrogen levels from 20% on one side of the repeater to less than 1% at the terminal. The sudden drop of hydrogen concentration from 5% to 0·5% along the 125 m length removed from the system suggested a gas blockage at, or very near, the fault position. Backscatter tests on board ship confirmed that all the faults had been removed from the recovered cable. Backscatter tests from the terminal station proved there were no fibre faults in the two halves of the system.

The rejointing of the recovered cable to the system, relaying to the buoy, recovery of the buoy, testing, and jointing of the two halves of the system together again, were deliberately carried out as one continuous operation to simulate realistically a North Sea repair operation. These operations were achieved in 35 hours and demanded a great deal of flexibility on the part of the staff involved as only short periods of rest were possible throughout the operation.

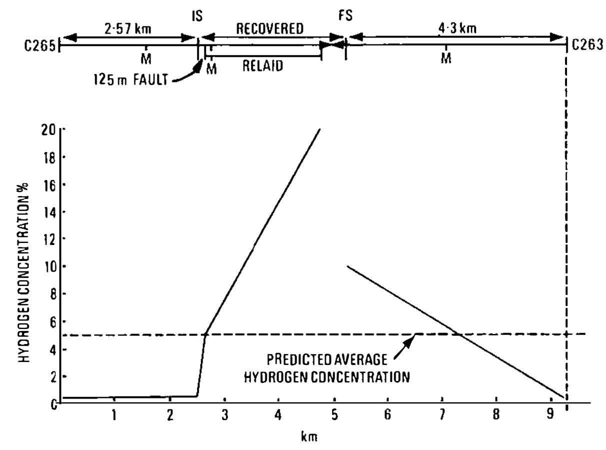
On completion of the repair, backscatter tests from the terminal confirmed that all six fibres were intact round the loop and that joint losses were acceptable. Despite the fact that the repeater had been removed from the system, power-feeding current was restored over the loop to maintain the conditions that prevailed before the repair. The terminal equipment was re-spliced to the line fibres and error-free transmission restored over the system.

Further visits to the station will be carried out to monitor the condition of the fibre loop.

FAULT INVESTIGATION

The 125 m length of recovered cable was returned to STC, where an investigation into the causes of the fault was carried out in conjunction with engineers from BTRL. Gas samples taken from each end of this sealed length confirmed the large disparity of hydrogen level measured during the repair. A known volume of gas was injected into one end of the sample and the pressure change recorded, and this indicated a gas blockage close to the position of the fibre breaks. Dissection of the entire length revealed that the aluminium tube had been crushed over a 27 m length, and that the helically laid fibres were trapped against the central king wire. The fault was undoubtedly caused by a most unusual form of external interference to the cable on the sea bed. Some external smooth object capable of exerting a force of 0·2–0·24 tonnes force per centimetre length had either rested on or slid along the cable. Since Loch Fyne is a submarine testing area, it is surmised that this might have been the cause. This form of cable construction has now been superseded by an improved and strengthened type with virtually no risk of fibre break without cable break.

Further investigations are being carried out on the recovered repeater and the recovered fibres from within the cable, and the measured hydrogen levels are being analysed to prove the validity of the mathematical hydrogen permeation models. On the assumption that hydrogen concentrations fall linearly with distance, it can be seen in Fig. 8 that the measured hydrogen levels are fairly close to the average predicted over the complete fibre length.



IS: Initial splice FS: Final splice M: Manufacturing joint

Fig. 8—Hydrogen concentration in Loch Fyne system

CONCLUSION

Many lessons were learnt from the Loch Fyne trial concerning cable design, and all potential weaknesses have been eliminated from the the current STC designs. Essentially, contra-lay strands have been provided to increase the tensile strength and crush resistance of the cable, the aluminium tube has been replaced with a copper tube to inhibit hydrogen reaching the fibre package, and water blocking of the fibre package and strand has been introduced to prevent water ingress. The copper tape over the steel strand has been eliminated as this contributed to cable weight and therefore cable strain without contributing to the cable performance. This new design of cable has been adopted for use on the UK–Belgium No. 5 system and the STC segment of TAT-8.

The early installation of the prototype submarine cable system in Loch Fyne has provided invaluable information into many problems which could not have been foreseen when the trial was first envisaged.

Biographies

Dick Ferris joined BT as a Trainee Technician Apprentice in 1961. On completion of his training, he transferred to the Submarine Systems Division to work in the Submerged Repeater Repair Laboratory, where he was promoted to Assistant Executive Engineer in 1969. He joined the Submerged Plant Group in 1972, dealing with all aspects of submerged plant on analogue submarine systems. He was promoted to Executive Engineer in 1980 and joined the Submarine System Technology Support Group in 1981, where he is responsible for monitoring the development of optical fibre, cable, joints, repeater terminations, and optical test equipment.

Ray Channon is an Executive Engineer in the Submarine Cable and Microwave Division of BTI. He joined BT in 1965 as a Trainee Technician Apprentice and, after completing his training, worked on the maintenance of the trunk transmission network in the Guildford Telephone Area. On promotion to Assistant Executive Engineer in 1975, he joined the Submarine Systems Division, and was involved initially in the commissioning of analogue coaxial cable systems, and then carried out planning studies, prepared specifications and adjudicated tenders for submarine cable systems. In 1978, he joined a newly formed group to monitor and oversee the development of optical-fibre submarine cable systems. In 1981, he was promoted within the optical-fibre group to his present grade, where his main responsibility has been to provide technical support for the planning and provision of optical-fibre submarine cable systems.

Integrated Circuits for Submarine Communication Systems, Their Design and Development

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Digital optical systems represent the current advance in submarine communications. Modern system designs require rapid evaluation of new components without relaxation of the stringent reliability requirements demanded for submarine applications. This article describes the development of integrated circuits (ICs) for submarine use. It goes on to show the design methodology, and discusses some limitations and the demanding reliability assurance aspects. The current IC designs are being used in both long-haul and short-haul links. The technology discussed is providing a major role in the future development of high-capacity optical submarine systems.

INTRODUCTION

Submarine communication systems demand positive assurance that all the required system functions will be successfully carried out and that they retain expected performance over a long lifetime. In submarine communication systems, the replacement of defective devices is both difficult and costly. It is therefore essential that only devices having an assured high reliability should be specified in these applications.

The exploitation of semiconductor devices in submarine systems has been the subject of research and development for many years. In early systems, coaxial cables were employed, and valves and transistors used to provide amplification for frequency division multiplex (FDM) working. Typically, these analogue systems used two amplifiers each with three transistors to provide two-way communications. This provision of six active devices in each repeater demanded exacting performance standards. With time, the system overall bandwidths have progressed from 4 to 45 MHz. The latter system used the Type 40 family of transistors and these devices are easily achieving their expected reliability.

With the introduction of optical-fibre technology and an ongoing demand for increased capacity and speeds of digital systems, the submarine-quality components are now following the general trend of operational speed, power constraint and increased complexity. Typically, the number of transistors now included in integrated circuits (ICs) is some 100 times greater in the present digital optical regenerator electronics than in analogue systems using discrete components.

This article covers the design and development of a family of emitter-coupled logic (ECL) gate array ICs. These ICs are currently being used in submerged optical communication systems operating at 280 Mbit/s. For the basic technology deployed, the design methodology and circuit development is outlined and some avenues of potential enhancements and limitations for future systems are explored.

CONSTRUCT ANALYSIS

A *construct analysis* approach to IC development has been adopted in which only fully-assessed circuit elements are used in the final chip design. The bipolar transistor technology employed for the manufacture of long-life discrete silicon planar transistors, denoted as *Type 40*[1], has provided the active elements in under-sea FDM systems of 45 MHz bandwidths. Such devices, which have been in service since 1976, offer good linearity, ruggedness[2, 3] and a 4 GHz transition frequency with 0·2 μm base widths. Fig. 1 shows the Type 40 C, with some 36 elemental transistors in a radial pattern to allow good thermal distribution.. The circular device, 250 μm in diameter, has 18 radial arms, each providing some 3·5 Ω emitter ballast resistances. Extensive accelerated life testing provides predicted lifetimes, at 60°C, as time-to-first-failure, of 1×10^9 years and $1{\cdot}6\times10^7$ years at the 99·9% confidence level, with an activation energy[4, 5] of 1·8–2·0 eV. Degradation caused by the reduction in carrier lifetimes is evident as a reduction in gain and increases in leakage currents I_{EBO} and I_{CBO}, and the measured failure distributions using high sample sizes (typically 500) relate well to the expected log-normal distribution model. These devices represent the foundation element for the new family of ICs.

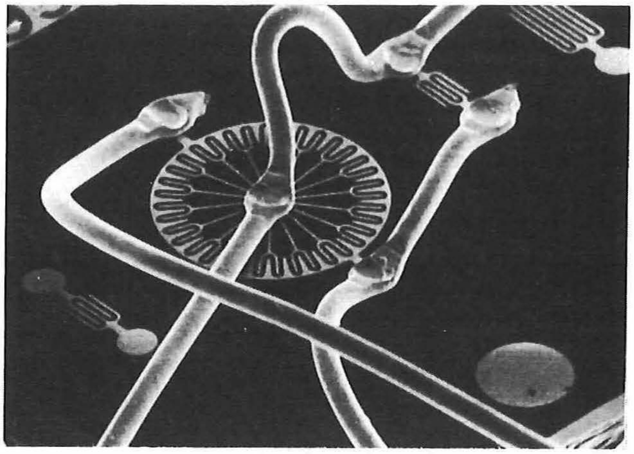

Fig. 1—Circular power transistor, Type 40 C, with single transistor providing emitter-base protection

Diffused resistors manufactured on special test wafers provide a test vehicle to demonstrate the longevity of resistor elements for inclusion in the IC family (Fig. 2). Based on the same process technology, such resistors can be integrated

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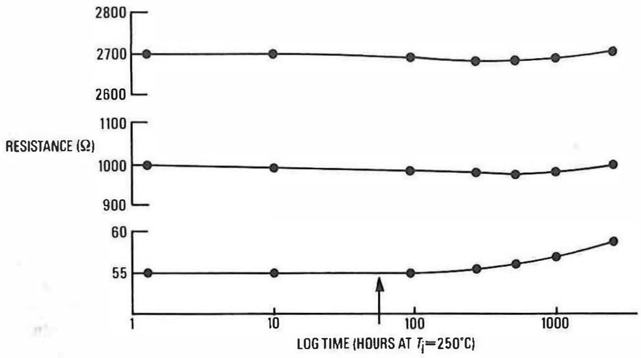


Note: Arrow indicates effective value at 25 years for an assumed activation energy of 0·8 eV

Fig. 2—Variation in elemental resistors at elevated temperature

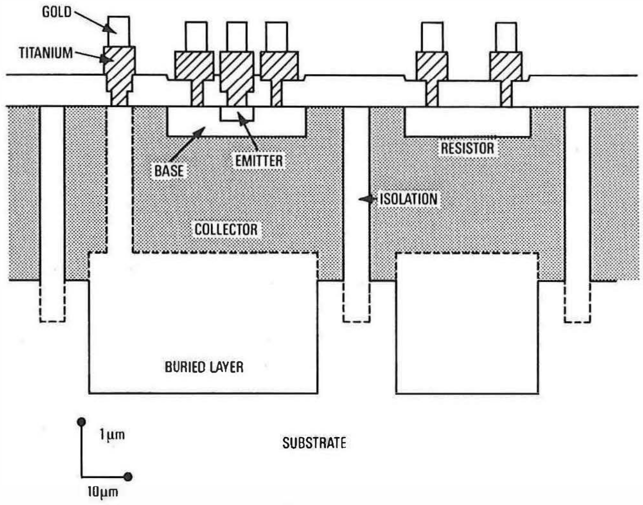
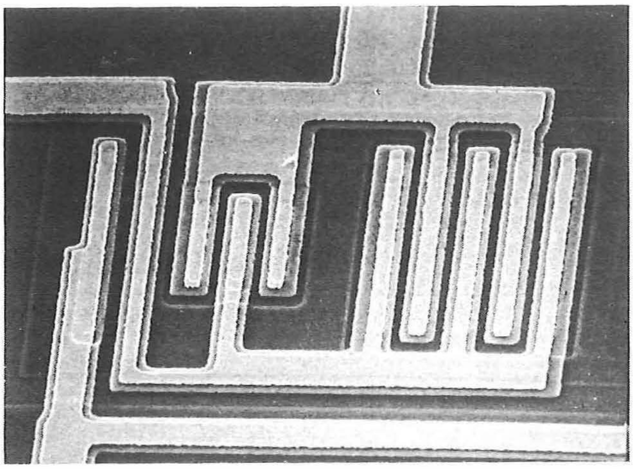


Fig. 3—Schematic section of isolated transistor and elemental resistor

by using the base diffusion through specific areas within a surrounding n type region connected to a positive supply; thereby a reversed-bias junction is established to ensure resistor isolation, as in Fig. 3. Components are isolated from each other by the use of a p type substrate and deep p type diffusions, which form reverse-bias junctions with the n type collector epitaxy and a buried layer. Collector contact to the active area is provided via an ion-implanted buried layer, which offers a low-resistance contact to an n type collector contact within the deep p type well. The critical processes of the transistor, which retains re-cut emitter contacts in a 5 μm emitter strip, therefore remain isolated from the additional elements. Interconnection can be provided with the proven titanium/gold metallisation system[1].

By using this technology, ECL arrays can be fabricated. These ECL arrays are used to construct a range of ICs having particular electrical features, and, in designing the arrays, consideration has been given to the required functions necessary for digital regeneration. In particular, an 8-cell array has been fabricated for application to submarine systems. In this array, the need for both digital and analogue circuit elements was recognised in an array providing eight logic cells, analogue elements and up to 24 power transistors. This combination has allowed the manufacture of ICs fully able to support the circuit designs required for digital regeneration, and these arrays have been exploited at operating rates of 1 GHz[6].

Other arrays allowing greater circuit complexity and integration levels are under development, but a feature of all these arrays is a process validation module (PVM) consisting of the basic Type 40 transistor element, Fig. 4. This elemental unit is able to contribute to the overall high level of process control and validation of the product by way of reliability exercises and parametric evaluations to demonstrate product homogeneity.



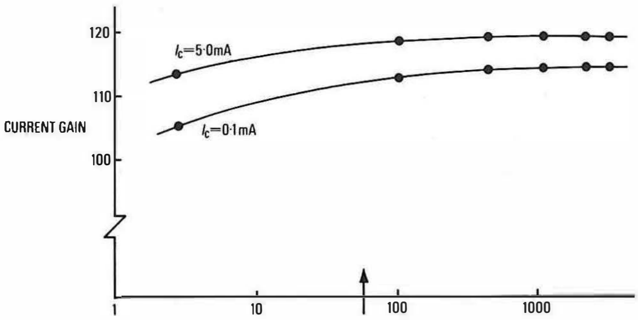
Note: A double emitter (×2 transistor), right, is coupled to a single emitter (×1 transistor), left, and a common-collector contact, far left

Fig. 4—Micrograph of process validation module (PVM) resident on the ECL 40 8-cell array chip

INTEGRATED CIRCUIT DESIGN

Methodology for 8-Cell Arrays

Electrical-circuit design with the 8-cell array can be undertaken manually as the layout complexity is relatively low. A set of design and layout rules is supplied to the electrical-circuit designer, together with detailed characterisations of all the array elements and the permitted current levels associated with the interconnect tracks. The layout can then be performed by the design engineer on a 3 μm grid-sheet representing a scaled diagram of the die of the uncommitted logic array (ULA). Simulation of the circuit functions can be made by the designer, if required, and the designs passed to the computer-aided design (CAD) toolsets within the Microelectronics Design and Applications Division at Martlesham. Also required at this stage are the user's electrical specification, pin-out details and test information. For applications to submarine systems, the simulations take into account the predicted end-of-life parameters, Figs. 2 and 5.



Note: Arrow indicates effective value at 25 years for an assumed activation energy of 0·8 eV

Fig. 5—Variation in elemental transistor gain at elevated temperature

By virtue of the array die layout contained in the CAD system, all the underlayer array details are automatically aligned for the particular circuit design. The electrical circuit determines the placement of overlayer metallic interconnections. Fig. 6 shows the design procedure. A high level of visual inspection is undertaken of the complete IC design and full checking of permitted interspacings and design rules are made before mask generation is permitted.

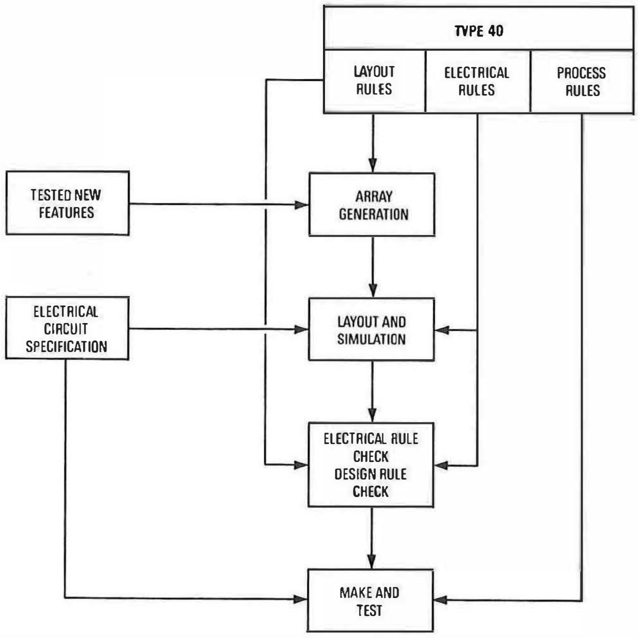


Fig. 6—ECL 40 Array design procedure

EMITTER-COUPLED LOGIC CIRCUITS

The features that ECL circuits[7] offer include:

(*a*) power dissipation which is independent of switching frequency,
(*b*) sub-nanosecond transition times,
(*c*) DC coupling and differential working, and
(*d*) high noise immunity resulting from inherent circuit balance.

The circuit of the basic ECL switch is shown in Fig. 7. The current source is realised as a current mirror by using another transistor. The output is buffered by using an emitter follower.

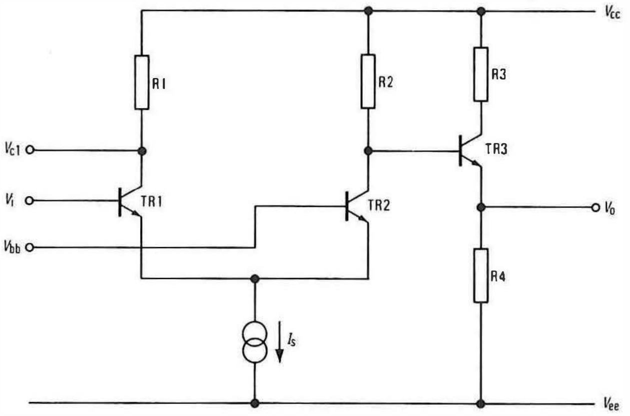


Fig. 7—Basic emitter-coupled switch and emitter follower, TR3

Hierarchical Design Elements

IC design can be seen as working on six levels:

1 Components (transistors, resistors).
2 ECL gates.
3 Simple logic blocks.
4 Larger logic blocks, such as the clocked bistable of Fig. 8, which occupies one cell of the 8-cell array.
5 Interface circuits.
6 The interconnection pattern.

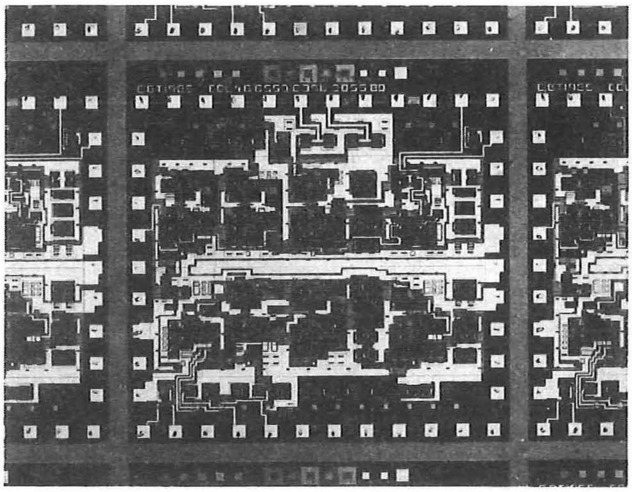


Fig. 8—8-cell array chip design providing retiming and supervisory gate functions

Circuit Types

The main-path regenerator electronics, integrated by using the ECL 40 8-cell array, demand a wide range of analogue and digital circuitry. These requirements can be achieved with a hierarchical approach and the layout method given earlier. These circuit requirements can be classified into the five broad categories given in Table 1.

TABLE 1
Categories of Circuit for Regenerator Electronics

Circuit Type	Typical Application	Salient Features
Wideband amplifiers	Data (automatic gain control) Clock (limiting)	Bandwidth greater than 300 MHz
Non-linear peak detector	Clock extraction	320 MHz output
Low-speed	Mean power controller for lasers	High current output
Emitter-coupled logic	D-type bistable Loop-back gate	Achieved operating frequency of 600 MHz
High power	Laser drive circuits	Sub-nanosecond transitions/high currents

LARGER CELL ARRAYS

To support increased circuit density and integration levels, other uncommitted arrays of 24, 80 and 128 cells have been developed. Table 2 gives brief details of these arrays, which have similar fabrication processes to the 8-cell array. Table 3 gives the chip sizes and maximum power dissipations. The metallisation system and design rule limitations of the 80-cell array are identical to the earlier 8-cell structure. However, to limit the total current demand of these ICs, the resistor values have been increased. They operate at lower speeds and are used in regenerator supervisory subsystems. Figs. 8 and 9 show examples of the metallisations of the 8-cell and 80-cell arrays.

TABLE 2
Uncommitted Logic Array Sizes

Cell Count	Clock Rate	Application	Features
†8	560 MHz	Regenerator analogue and digital circuits	5 µm geometry, single-layer Ti/Au interconnections
24	1 GHz	Regenerator analogue and digital circuits	3 µm geometry, single-layer interconnections
†80	280 MHz	Regenerator digital circuits	5 µm geometry, single-layer Ti/Au interconnections (plus 20 additional housekeeping cells)
128	400 MHz	Digital circuits	5 µm geometry, two-layer interconnections (plus 32 additional housekeeping cells)

† Arrays in current submarine systems

TABLE 3
ECL 40 Array Power Dissipations

Array Size	Power Maximum (design rule limit in watts)	Die Size (mm)	Power (kW/m^2)
8-cell	0·5	2·2×2·2	103
24-cell	2·0	2·5×4·5	178
80-cell	1·5	5·4×5·4	51
128-cell	4·5	4·5×4·5	222

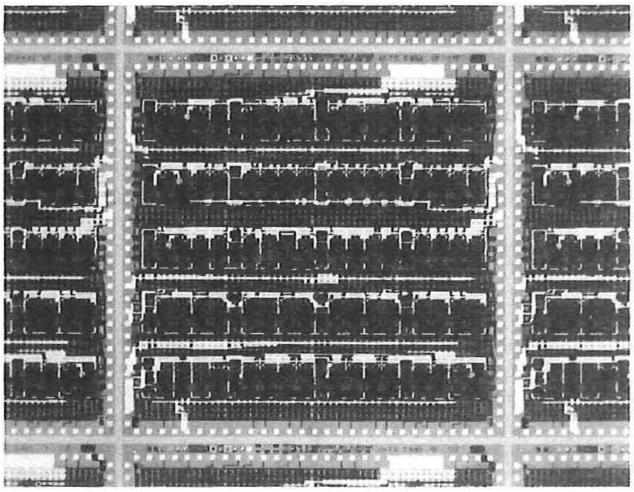


Fig. 9—Command decoder chip using the 80-cell array

SIMULATION MODELS

The simulation exercise requires an electrical description of the IC design as information to model the circuit, the input stimuli and models of the primitive elements. The output consists of waveforms at circuit nodes in response to the inputs applied. For digital circuits, functional and performance simulation is used to demonstrate working at correct speeds, and that the design is race and hazard free.

In the case of devices for submarine systems, both digital and analogue simulations are required and the integrity of the simulation depends upon the quality of characterisation of the elements of the arrays. The expected variations in element parameter values need to be known throughout the expected 25-year life of the system. Figs. 2 and 5 show the predicted variations in resistance values and transistor gain obtained by operating devices at elevated temperatures. To gain the high assurance levels needed for these ICs, circuit verification is used. Here the electrical circuit design is modelled at the component level and the circuit evaluated for DC and small-signal AC behaviour. Fig. 10 shows the schematic of a clocked bistable, which would occupy one cell in the 8-cell array. A typical simulated output waveform for this circuit is compared with its measured performance in Fig. 11. A representative simulation tool is SPICE, which was originally developed at the University of California at Berkeley, and which uses models related to the physics of devices. An advantage of SPICE is that allowances for parameter temperature effects can be made. By using this program, the expected drift rates and temperature variation effects can be simulated for each IC, and for large parts of the complete regenerator electronics, to provide confidence

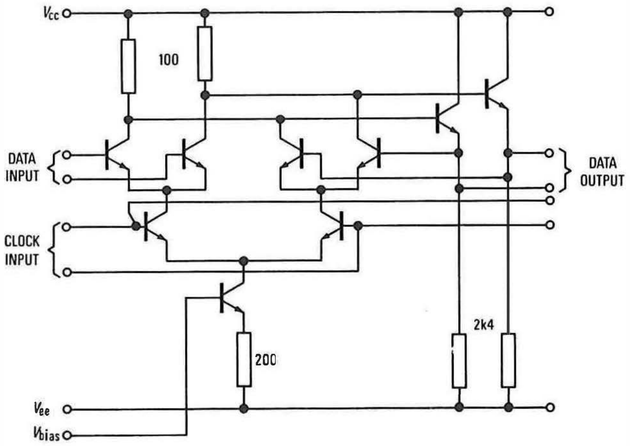


Fig. 10—Schematic of clocked bistable occupying one cell of the 8-cell array

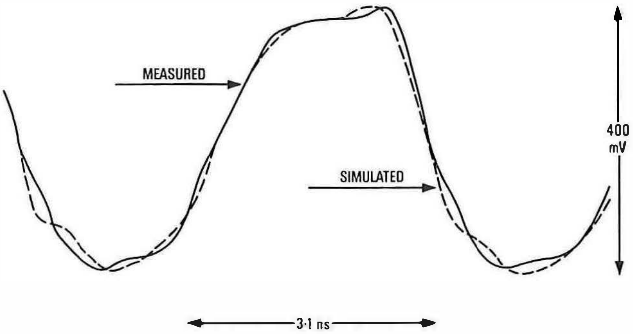


Fig. 11—Measured and simulated output of master/slave D-type bistable at 320 Mbit/s

in the long-term system performance. Alternatives to SPICE include ASTEC, which provides similar types of analysis but allows for statistical variations in circuit components, has some speed advantages and allows the users to define their own component models. Representative SPICE input data for the Gummel-Poon model[8] is shown in Table 4 for a transistor in the 8-cell array and a scaled input transistor used with the full-custom IC used in an optical receiver module[9]. In the design of ICs used to support the digital supervisory subsystem in STC's NL2 system[10], the simulation program ASTAP, developed by IBM, was used; the program allows user-defined models and provides the expected timing diagrams and the designed logic sequences.

TABLE 4

SPICE Model Parameters, for a Single Transistor used in the 8-Cell Array and the Scaled Input Transistor for the Custom IC

Parameter Description		Values		Unit
		Standard	Reduced	
Emitter area	$(L \times W)$	25×5	15×5	μm^2
Capacitance e–b	(C_{Je})	0·33	0·20	pF
Capacitance b–c	(C_{Jc})	0·27	0·13	pF
Capacitance to substrate	(C_{cs})	0·30	0·19	pF
Capacitance of input bond pad	(C_{pad})	0·40	0·18	pF
Capacitance input track (typical)	(C_{track})	0·20	0·05	pF
Bond pad area	(A_{pad})	75×75	50×50	μm^2
Common emitter gain	(β)	60	150	-
Forward transit time	(τ_f)	31	21	ps
Total base resistance	(R_{bb})	115	500	Ω

INTEGRATED WORKSTATIONS

The integrated workstation provides a full integrated custom computer-aided engineering (CAE) system able to support designs of considerable complexity; current CAE workstations can cope with 10^6 transistors per IC. A feature of workstations is that, in one machine, they house the following capabilities:

(*a*) interactive schematic entry;
(*b*) logic, analogue and fault simulations; and
(*c*) automatic placement and routing programmes that provide mask-pattern generation data leading to designs in silicon that are initially correct.

These machines store fully characterised and proven library circuit blocks for inclusion into designs.

Such workstations allow the toolsets and design facilities to be used by system development engineers, and thereby this reduces product development time and allows only fully checked designs to reach the manufacturing stage. Fig. 12 illustrates the type of workstation used to complete the design shown in Fig. 9; this design required a high utilisation of the 80-cell array.

In using the workstation approach, the base array design is stored, and particular metallisations to commit the array are correctly located. This correct-by-construction approach enables a final design to be verified without resort to external toolsets. Typical resident toolsets include simulations, mentioned earlier, network connectivity checkers, design rule checkers and electrical rule checkers, each working from the input schematic design information.

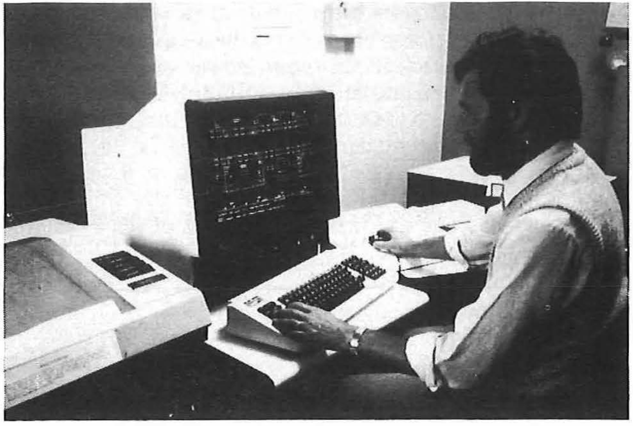


Fig. 12—Workstation used for IC design

Placement and Routing

Automatic placement and routing is an important feature of the workstation because it shortens layout times and ensures their correctness. The possibility of manual intervention, however, allows optimisation aimed at reduction in parasitics on critical circuits to be undertaken.

Checkers

Just as word processors contain spelling checkers that reveal errors but cannot detect malapropism or punctuation faults, so design checkers are also limited in their capabilities. However, they do show all potential errors, and interpretation is required to discern what is permitted and what appears as an error.

Electrical Rule Check

The electrical rule check (ERC) is undertaken to verify that electrical engineering principles are not violated and that the circuit structure is not outside established electrical rules; for example, that the number of loads on driver stages is not exceeded, that outputs are not tied together or to supply points and that no unconnected or floating terminations exist. ERC might show a connection to an unused transistor in the array and a design change would be required that could be speedily undertaken without added cost of the silicon fabrication stage.

Design Rule Check

The design rule check affords protection against generation of masks containing errors where the design rules are violated; that is, where track widths are outside the permitted limits and track locations are outside the correct spacings with respect to other array components. Clearly, the base array topology determines the reference locations for permitted track placements.

Network Connectivity Check

The network connectivity checker generates a network listing from the input schematic, the same schematic used in simulations, and compares it with a network listing obtained from the final derived metallisation layout. In the arrays, diffused cross-unders are employed; these allow an isolated low-conducting path below, and insulated from, an overpassing track. Interpretation of the differences between the two network listings would here show a track discontinuity, but information on these permitted connections can be in-built. As all differences between the network listings are generated, in a successful design no differences would exist.

WAFER FABRICATION

Wafer manufacture is undertaken in special clean-room environmental conditions. The wafer fabrication processes developed by the VLSI Division of Research Department follow a plan consisting of more than 80 individual processes to fabricate the basic arrays prior to metallisation. The proven titanium-gold metallisation system, developed for the Type 40 transistor, requires an additional 15 processes before the in-built array components become a dedicated IC design.

The processing is controlled to the stringent quality levels necessary for submarine system components[11]. The overall sequence of process steps is divided into logical blocks, and audit points are installed to demonstrate compliance with manufacturing specifications before wafers can progress to their next operation. As wafer traceability, and eventual die and package traceability, is required, a highly developed control system is used to provide an entry for recording process results against process specifications and operator instructions for each stage. This interactive real-time system gives the location of parameters and test result values used in the authentication of each manufactured IC, as well as monitoring and progressing wafer batches through the fabrication plant.

IC PACKAGES

The hermetic package provides a secure environment for the successful operation of each chip and thereby contributes to the long-term reliability requirement of submarine ICs. The hermetic packages are composed of a ceramic base substrate, with a metallised area to accept the die attachment, to which two walled sections are applied. The top wall is made thinner than the lower wall so that refractory metal tracks placed on the formed plateau can pass between the two walls. The upper surface of the top wall is also plated with a refractory metal, before the assembly is fired, to allow the green-state ceramic to form an integrated whole. After firing, the metallised areas are nickel- and finally gold-plated, Fig. 13.

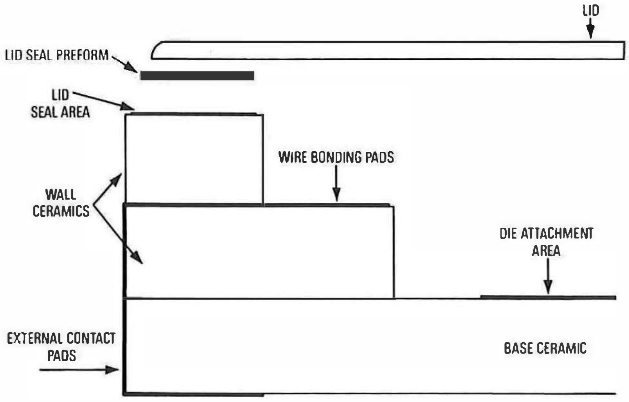
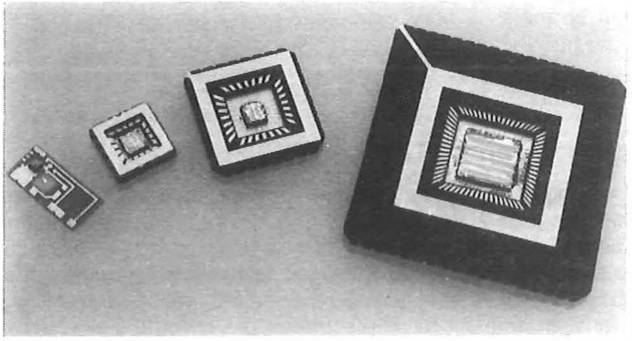


Fig. 13—Section of package edge, showing multilayer ceramic construction

The silicon die is attached to the base substrate by a eutectic braze formed between the plated surface, an inserted preform and the rear surface of the die. After gold-wire bonding between the die bond-pads and the package pads, the package is lidded by the formation of a tin/gold eutectic braze between the top side wall and a gold-plated metal lid. To secure a good working environment, the package is sealed to provide a dry nitrogen atmosphere within the package cavity. With this type of construction, leaks can develop at the formed lead seal or around the lid edges. Such leaks would allow moisture and contaminants to find their way into the package assembly and might result in degradation of the IC. Fig. 14 shows the unsealed chip-carrier packages currently used in submarine applications, together with the sub-mounting used with the full custom receiver chip, which is also used in a hermetically sealed package.



Left to right, full custom IC chip mounted on a substrate,
18-pin leadless chip carrier with 8-cell array,
24-pin leadless chip carrier with 8-cell array,
68-pin leadless chip carrier with 80-cell array

Fig. 14—Uncapped ceramic chip carriers

IC Package Leak Testing

Checking the integrity of the package seal on hermetic devices is a critical part of the assembly quality-control function and, in processing devices for submarine application, extensive hermeticity testing is carried out.

Details and limitations of hermeticity testing are covered elsewhere[12] and production experience over more than three years shows that the requirements for submarine-quality component are being achieved, Table 5.

TABLE 5

ECL 40 Hermeticity
(results of hermeticity testing on 18-pin leadless chip carriers used to house the 8-cell array products)

Specification requirements	5×10^{-8} bar cm^3/s
Production achievements	$<5 \times 10^{-9}$ bar cm^3/s
Demonstrated sample measurements, by radio-krypton test	$<1 \times 10^{-11}$ bar cm^3/s

HIGHER LEVELS OF INTEGRATION

For many years, the driving force behind IC technology has been the reduction of physical dimensions, and this has led to more chips per wafer and hence lower cost, increased performance and increased chip complexity. In the demand for higher performance and greater reliability from submarine ICs, higher levels of integration are also expected and increased functional density is required.

A number of possible methods exist for increasing the level of integration and speed of ECL circuits. One solution is an increase in the number of logic blocks per microcircuit die. This demands larger chip sizes and gives higher power dissipation levels, resulting in higher operating temperatures with a consequent reliability penalty. The need to dissipate more heat is reflected in the design of the IC package because lower thermal impedance packaging and mounting techniques are required. In addition, higher numbers of package pin-outs are required, which increase package parasitic effects. Further pin-outs are needed to allow testing to assure correct working of the logic blocks. This therefore dictates that the IC design is governed by heat dissipation limits and pin-out availability.

Accepting these limitations could compromise the speed of operation because of parasitics, but, if operational speed is not critical, an increase in the integrated resistor values can be made to overcome some power limitations. A representative example of this higher-resistance approach has been used in the 80-cell array designed to support the all-digital NL2 supervisory system[10].

SPEED LIMITATIONS

The speed of a circuit is determined by the particular configuration as well as the number, and type, of transistor and passive elements used. There are speed limitations due to the transistors themselves and to parasitic effects of the circuit elements, such as resistors and interconnection tracks. The switching speed of the transistors is limited primarily by the base resistance, R_b, and the junction capacitances. Considering the small-signal maximum operating frequency, f_{max}, then,

$$f_{max} = f_T/(8\pi R_b C_{bc})^{1/2}$$

where C_{bc} is the collector capacitance and f_T is the cut-off frequency. For a given transistor fabrication technology, f_T is set, and, to gain enhanced speeds, an increased f_T would be required; this can be achieved with reduced base-widths.

ICs IN CURRENT SUBMARINE SYSTEMS

The application of ECL 40 bipolar technology to present submarine systems falls into three categories:

(*a*) small arrays, 8-cell, used for regeneration electronics and supervisory interface circuitry;

(*b*) medium-size arrays, 80-cell, supporting the digital supervisory system and designed using the workstation approach; and

(*c*) a transimpedance amplifier[13], a full custom circuit used in conjunction with a PIN diode detector, and housed in a hermetic receiver module, operating at 320 Mbit/s. This IC uses a reduced-emitter-length transistor as the input element to achieve reduced capacitance, and a reduced-length input track feeder. The parameters used with SPICE are shown in Table 4. This circuit follows a similar production route, Fig. 15, but requires a full custom approach using its own set of nine dedicated masks in fabrication.

TEST AND VERIFICATION

Even with extreme control of manufacturing conditions and materials, sporadic unreliability can occur. This is usually attributed to aberrations in microcircuit manufacture. Although sound design, process validation and effective quality control exist in the production of submarine-quality ICs, any devices with a propensity for early failure must be eliminated.

All ICs are subjected to extensive screening and only wafers from which sampled PVMs have successfully demonstrated their reliability by high temperature step-stressing are used. The major screen temperature elements are storage and burn-in[14], and, during burn-in, each IC design is functionally biased, Fig. 16. Included in the screen are dew-point measurements, to ensure that water vapour is excluded from the package; DC parametric studies made on the PVMs; functionality tests and hermeticity tests (gross and fine leakage). Full functional measurements on each IC, and its PVM, are undertaken at 25°C and the results used to evaluate the effectiveness of the screen. Only ICs demonstrated to have stayed within strict and established screen limits and fully meeting their specified performance are allocated to operational life test. Here more than 1000 hours

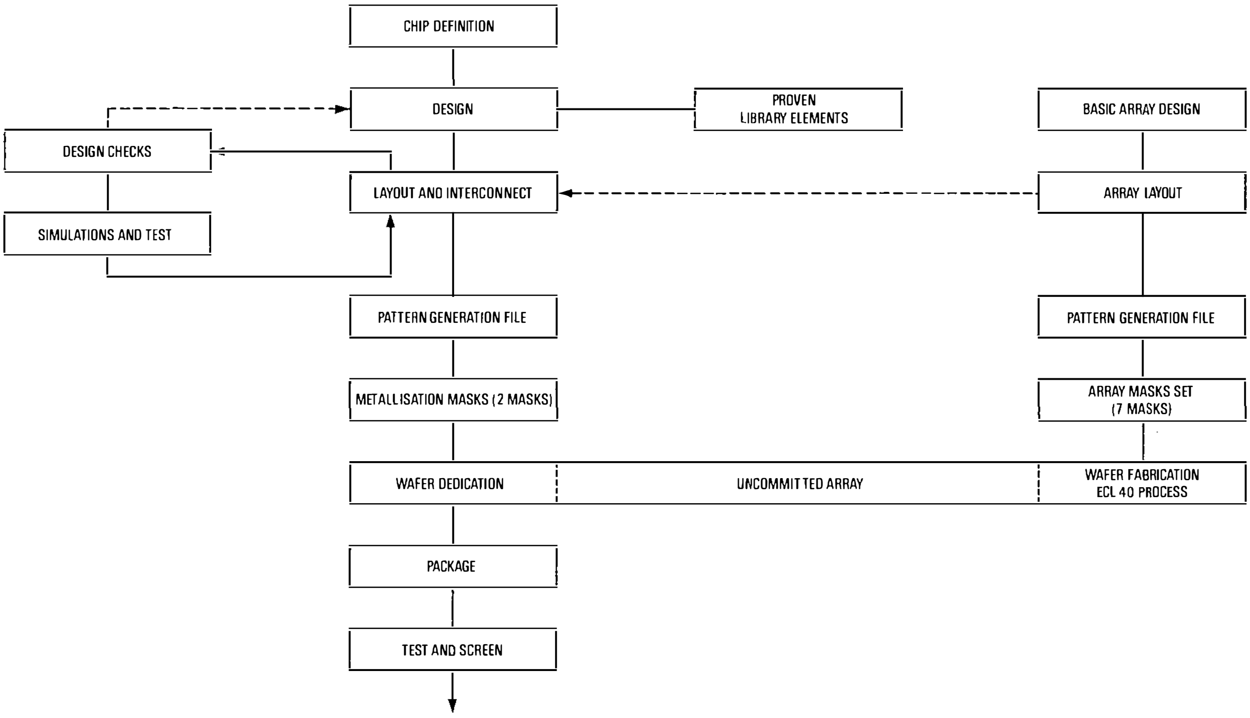


Fig. 15—Design and manufacture route for ECL products

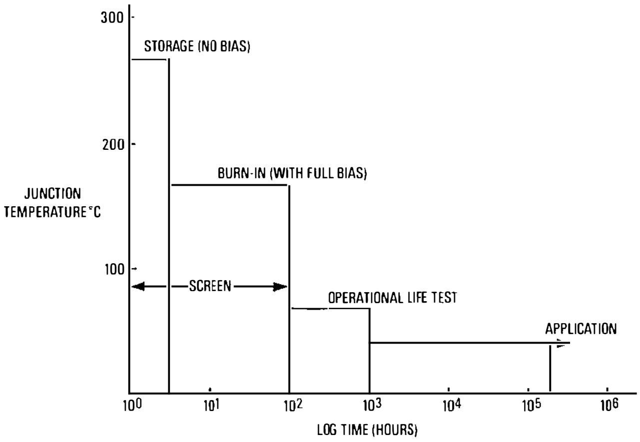


Fig. 16—ECL 40 post-assembly temperature profile

of operation without performance change must be achieved. Other ICs from each production batch are operated at 2°C as a confidence test to ensure against failure mechanisms not accelerated at high temperatures. Further samples are given mechanical tests.

Only those ICs which comply fully with the requirements of manufacture, package, testing stages, and operational life test can be considered for release for application in submarine systems.

IC RELIABILITY

A vital adjunct to the testing of submarine-quality ICs is assurance that reliability targets can be achieved. Reliability engineering demands that the quest for reliability permeates all the design and production processes. For this reason, the construct approach outlined here has been used to demonstrate that all new features were fully characterised and employed conservative design rules. The ECL 40 family of devices has an additional isolation and collector contact to the original Type 40 transistors. Extensive qualification testing has shown that no excessive leakage current degradation has been introduced by this change and that no significant gain degradation occurs by a change to the reverse emitter-base bias. Also, a demonstration has shown that, although additional interconnection track lengths are required and an increased number of oxide steps must be traversed, metallisation migration will not occur.

For bipolar transistors, the potential failure mechanisms, listed in Table 6, can be accelerated, mainly by temperature. A comprehensive reliability evaluation can therefore be undertaken within reasonable timescales, by temperature overstress, to ensure the long-term reliability of the ICs.

To achieve the high reliability required for submarine systems, a reliability target must be allocated to individual component types, and this allocation reflects upon the system design philosophy. In the present design of submarine systems, the ICs for the main signal path require a demonstrated reliability of better than 10 FIT†.

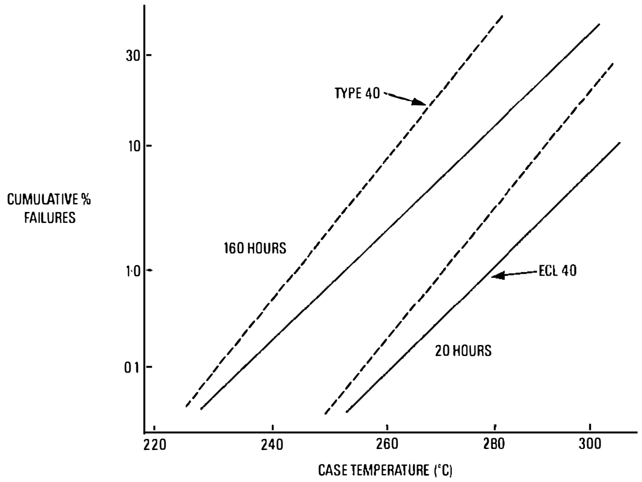
TABLE 6

Potential Failure Mechanisms

Failure Mechanisms	Accelerated by—
Bulk Failures	
Secondary Breakdown	Temperature, voltage
Metallisation Failures	
Electromigration	Temperature, current
Corrosion	Temperature, water vapour
Other material interaction	Temperature
Interface Failures Si and Si/SiO_2	
Dielectric breakdown	Temperature, voltage
Surface charge accumulation	Temperature, voltage
Charge injection	Temperature, voltage
Bonding Failure	
Intermetallic growth	Temperature
Bond-wire failure	Temperature, current, vibration and shock
Thermal fatigue	Temperature cycling
Die Mount Failure	
Thermal fatigue	Temperature cycling

Overstress Testing

The major problem in providing verification of high reliability is the difficulty in accumulating sufficient data, even with no failures, to statistically demonstrate a requirement level. The classical method to overcome this problem is to accelerate the failure mechanism by increasing the stress level above that expected in normal use. This acceleration assumes that the relationship between failure rates and stress levels is valid over the range considered. Interpolation between selected high-level points can be exact, but extrapolation beyond the selected range is dubious unless additional tests, designed to show that the relationship holds, are undertaken. In order to establish if the Arrhenius relationship[5] applies, a plot of $\log_e$ (failure rate) against the reciprocal of temperature is made. A straight line indicates a known relationship, for the particular temperature range. For the PVM, a comparison can be made between the transistor elements of the ECL 40 arrays with the Type 40 transistor. Fig. 17 shows the result of increasing the stress levels for two duration times, 20 and 160 hours, at each step and with case temperatures of 202, 234, 255, 277 and 298°C. Superimposed on Fig. 17 is the data for the Type 40 transistor and, whilst a straight-line relationship holds, it is evident that ECL 40 has a slightly increased (better) activation energy. Failure for these tests is defined, as for the original Type 40, as a gain change of ±50% or a leakage



ECL estimated activation energy = 1·9 eV
Type 40 estimated activation energy = 1·8 eV

Fig. 17—ECL 40 step stress data (compared with Type 40 transistor)

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† *FIT* refers to *failures in time*, and can be determined from:

FIT rate
= (number of failures/effective number of device hours)$\times 10^9$.

change of greater than 2 μA for I_{EBO}, I_{CBO} and I_{CEO}; the reliability target for the Type 40 was less than 0·02% failures in 25 years (10 FIT).

The step-stressing of sample PVMs from each production wafer affords a fast assessment of the potential reliability performance to be expected from the final product. In order to ensure that the ruggedness of ECL 40 transistors is comparable with the Type 40, a ×2 current overrating is used in the step-stressing of ECL 40 transistors. This factor provides an added degree of assurance against metal electromigration.

IC RELIABILITY DEMONSTRATION

A demonstration of ECL 40 reliability has been undertaken in two phases, the first being the construct approach, outlined earlier, and an exercise consisting of the accumulation of operational device hours and an accelerated life test. Both parts of the second phase are still continuing and will enable the main signal-path electronics, the supervisory digital electronics and the full custom receiver chip to be assessed.

Extended Operational Life Test

The purpose of this test is to demonstrate the performance of fully operational samples at a case temperature of 80°C. The aim is to accumulate more than 1·5 million device hours for the family of main-path ICs, and some 0·75 million device hours for each of the supervision and custom chips. The information gained will contribute towards a statistical determination of expected life times.

Accelerated Life Test

The objective of the accelerated life test is to fully exercise individual ICs at two elevated temperatures and to observe the circuit performance changes and possible failure mechanisms. Some 2·4 million device hours on the 8-cell array designs and similarly high device hours for the other ECL products are needed to assess their performance degradation and failure criteria.

The objective of the complete testing programmes is to explore and evaluate the associated activation energies of failure mechanisms and to calculate the failure rate for the various IC families. A reliability target of 10 FIT has been set for the 8-cell ICs with an expectation of 5 FIT.

REQUIREMENTS FOR NEXT-GENERATION SYSTEMS

Two significant directions are available in the near future. Firstly, increased equivalent circuit bandwidths will require higher speeds from the ICs providing digital regeneration. Systems operating at 565 Mbit/s, 1·2 Gbit/s and beyond, which are finding application in land systems, could be used in submarine applications when suitable reliability has been demonstrated. A family of array-based ICs for higher-speed working and now being applied in 565 Mbit/s inland systems support this approach as they are generically derived from the same ECL technology. The second direction reflects the capability that digital/optical systems offer in enhanced networking. Typically, the capability of undersea branching networks, being proven for the transatlantic system TAT-8, coupled with the development of integrated services digital networks (ISDNs) world-wide, could allow combination and distribution of different data rates from a common system. The prospect of full interworking between nations would demand high levels of performance from the overall system and the IC designs from the error-rate and jitter viewpoint. The current design aids and toolsets now being used are well able to support the design requirements of both increased circuit density and enhanced process technologies which will be required for IC components for future very-high-data-rate systems.

In the longer term, the potential of the solid-state light amplifier and selective optical wavelength working suggest that increased circuit capacity can be achieved beyond the current state of developed and developing systems.

CONCLUSION

Born in the early-1970s, the Type 40 transistor has already spawned many descendants in the form of a family of ECL uncommitted arrays. The first generation of optical submarine communication systems employed the developed 8-cell arrays; current systems, typically the NL2 supervisory subsystem used in TAT-8, employ 8-cell array ICs and the 80-cell array ICs.

A family of ICs has been constructed which have an inbuilt assurance of longevity. Such ICs based on gate arrays are providing the necessary electrical circuit units to switch at sub-nanosecond rates, to provide clock, decision and timing circuits, as well as wideband analogue amplifiers needed for current and future systems. By the integration of the proven technology used in the Type 40, the accumulated life prediction work for the discrete transistor can be related to the new IC family by comparison of the PVM performance. Coupled to the ongoing evaluation of PVMs, as part of the manufacture philosophy, a comprehensive reliability work programme is under way. The reliability programme is aimed at demonstrating the expected longevity of these ICs so that the real-time in-service performance of the Type 40, now less than 10 FIT, can be achieved or bettered in current and future submerged communication systems.

The increasing demand for ICs for developing communication systems has been the motivation behind the now popular array concept. These arrays, coupled to the advances in CAD tools and design methodologies, enable electrical circuit designs to be rapidly constructed onto silicon without the need for, say, transistor-transistor logic and printed-circuit board modelling. The combined ability to have speedy design, fabrication and prototyping on an array able to support the eventual fully qualified ICs for application in under-sea communications is playing a major role in the further development of high-capacity optical submarine systems.

ACKNOWLEDGEMENTS

The author wishes to record that the work described embodies the efforts of many individuals within the Microelectronics Divisions of British Telecom Research Laboratories and STC Submarine Systems Limited. Acknowledgement is also made to the Director of Research for permission to publish this paper and to Submarine Systems Limited for permission to show Fig. 8, a circuit design using an 8-cell array.

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Biography

John Tew joined the Wireless Experimental Branch at Dollis Hill in 1954 as a Youth-in-Training. Since 1962, apart from a short period in personnel, he has been associated with the characterisation, testing and manufacture of high-reliability devices for submarine applications. He is currently Head of the ECL 40 Development and VLSI Production Control Section with the Microelectronics Design and Applications Division within Technology Executive.

Components for Submerged Repeaters and Their Qualification

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UDC 621.315.28 : 621.391.63

This article gives an overview of the reliability aspects of submerged repeaters and their components for optical submarine systems, with particular reference to the qualification and type-approval procedures that have been adopted.

INTRODUCTION

The reliability of submarine communication systems is critically dependent upon the design, performance and quality of components included in their construction. This applies equally to fibre-optic technology as to previous technology. The overall demand for high reliability is not altered, and a specific reliability target, typically three failures in 25 years for an intercontinental-length system, is set. These failures exclude those due to external hazards.

In order to achieve the set targets for the overall system, the reliability for the constituent parts must be apportioned. It therefore follows that each component type is allocated a reliability target which has to be demonstrated to an acceptable confidence level. The advent of fibre-optic systems has introduced new components to the submarine communication engineering technology which require qualification.

This article describes briefly the range of components, their reliability aspects and the methods used to demonstrate qualification to submarine-system standards.

SYSTEM AND COMPONENT TARGETS

A submarine system can be considered as being built up from basic elements connected either serially or in parallel.

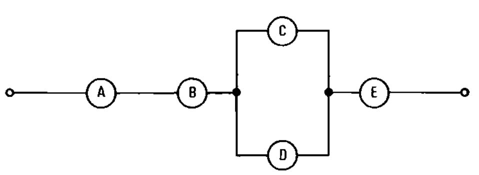

Fig. 1—Typical system, with serial and parallel elements, for reliability calculations

In Fig. 1, units A through E are basic parts to which some reliability figure is attributed, and the probability of failure in a given interval for each unit is P_A, P_B. . . .P_E.

If $P_C = P_D$, where C and D are included in parallel to provide some degree of redundancy, to improve reliability, and each component acts independently, the failure probability, P, for the overall system is given by

$$P = P_A + P_B + P_C^2 + P_E,$$

and the system reliability, R, is given by

$$R = 1 - P.$$

It is therefore possible to consider the overall system requirements and to determine the necessary failure probability of all the elements included. These unit failure probabilities are required for each component used. Whilst this simplistic approach shows the benefit of some redundancy, the inclusion of additional components has a cost/power

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penalty. It is necessary to approach system design in such a way that the elements with lower reliability are additionally supported by using redundancy techniques so that the overall system reliability target and performance can be achieved. As a result of the particular design philosophies used, the apportionment of reliability to components can be made. In the field of submarine communication systems, the component reliability targets are, of necessity, the most stringent in the electronics industry.

With few exceptions, the generations of coaxial frequency division multiplex (FDM) systems employed a bidirectional amplifying repeater. Each amplifier consisted of three transistors and about 100 other components. Therefore, in a system using n repeaters, a total component count would be typically

$$n(2 \times 3 \text{ transistors} + 2 \times 100 \text{ components}),$$

without considering additional supervisory aspects. In current digital optical systems, the number of transistors (with integrated resistors included in integrated circuits) is increased by a factor of about 100, and the other component count is roughly unchanged.

This increase reflects the change in technology, but the reliability requirements are exacting. Also, as these are new components, without established history in the submarine field, unprecedented demands are made to qualify these new components in short time-scales.

A typical reliability figure for a commercial diode is 80 FIT†. Components used in submerged repeaters require a low failure expectation; the cumulative hazard* and failure rates for current submarine components are shown in Table 1.

TABLE 1
Typical Failure Rates for Regenerator Components

Device	Failure Rate (FIT)	Cumulative Hazard (25 years)
Integrated circuits	5	0·0011
Surface acoustic wave filters	5	0·0011
Zener diodes	10	0·0022
Optical receivers	40	0·0088
Optical transmitters	107	0·0231

In undersea communication systems, components of only the highest integrity are used. Defective components cannot be replaced in systems of this nature without exceptional cost; therefore, infant mortalities must be eliminated by effective screening, and the reliability of such components must be demonstrated and their performance with time assured. This demands stringent and dedicated production methods that allow the highest quality components to be manufactured. These components are then subjected to accelerated life testing, mechanical and environmental tests in order to determine possible failure mechanisms and their characteristic life behavioural patterns. Hence, all components require a dedicated approach to process control, reliability improvement, high levels of assurance and exercises to undertake failure analyses leading to enhanced designs and improved manufacturing, screening and testing methods. Fig. 2 outlines the stages that must be followed in order to ensure a successful outcome.

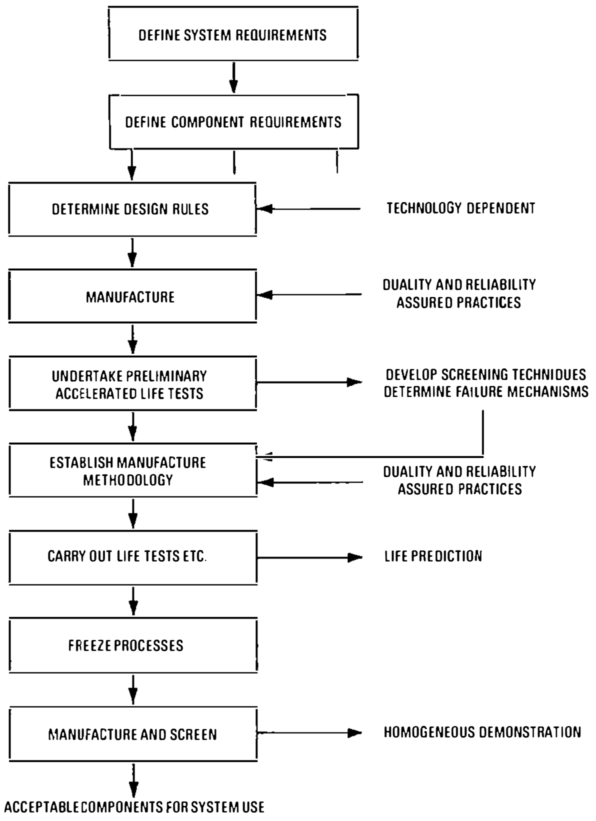

Fig. 2—Sequence of events necessary to establish system reliability requirements

QUALIFICATION AND TYPE APPROVAL

System operators or end users of submarine cable systems generally require that systems and their component parts are qualified or type approved to in-house specifications. For systems operated by British Telecom (BT), the route leading to type approval is given in Fig. 3, which shows the steps necessary to take an item from its conception right through to the issue of a type-approval certificate[1, 2]. It should be noted that it is not imperative to keep rigidly to the sequence of events, but rather to adhere to the overall concept.

The qualification of repeaters, which include several regenerator modules and their associated power modules, may be said to start with engineering audits and quality audits of each individual new component, including thick-film hybrid circuits, laser and receiver packages, manufactured either by the contractor or by subcontractors.

If the audits are satisfactory, permission is normally given by BT International (BTI) for the manufacture of the requisite number of qualification samples in accordance with the agreed qualification test plan. The manufacture of system components may also be commenced at this point. In addition, a considerable number of components are manufactured for use on life tests in order to demonstrate reliability. The final stage of the repeater qualification involves subjecting regenerator module pairs to a comprehensive range of tests to ascertain compliance with the requirements of the regenerator specification.

Documentation, such as drawings and specifications of components and modules, is submitted to BTI for approval in the course of the work outlined above.

ENGINEERING AND QUALITY AUDITS

Normally, engineering and quality audits take the form of joint audits when the component is manufactured by a subcontractor. The word 'joint' refers to the fact that auditing teams from both the contractor and BTI take part.

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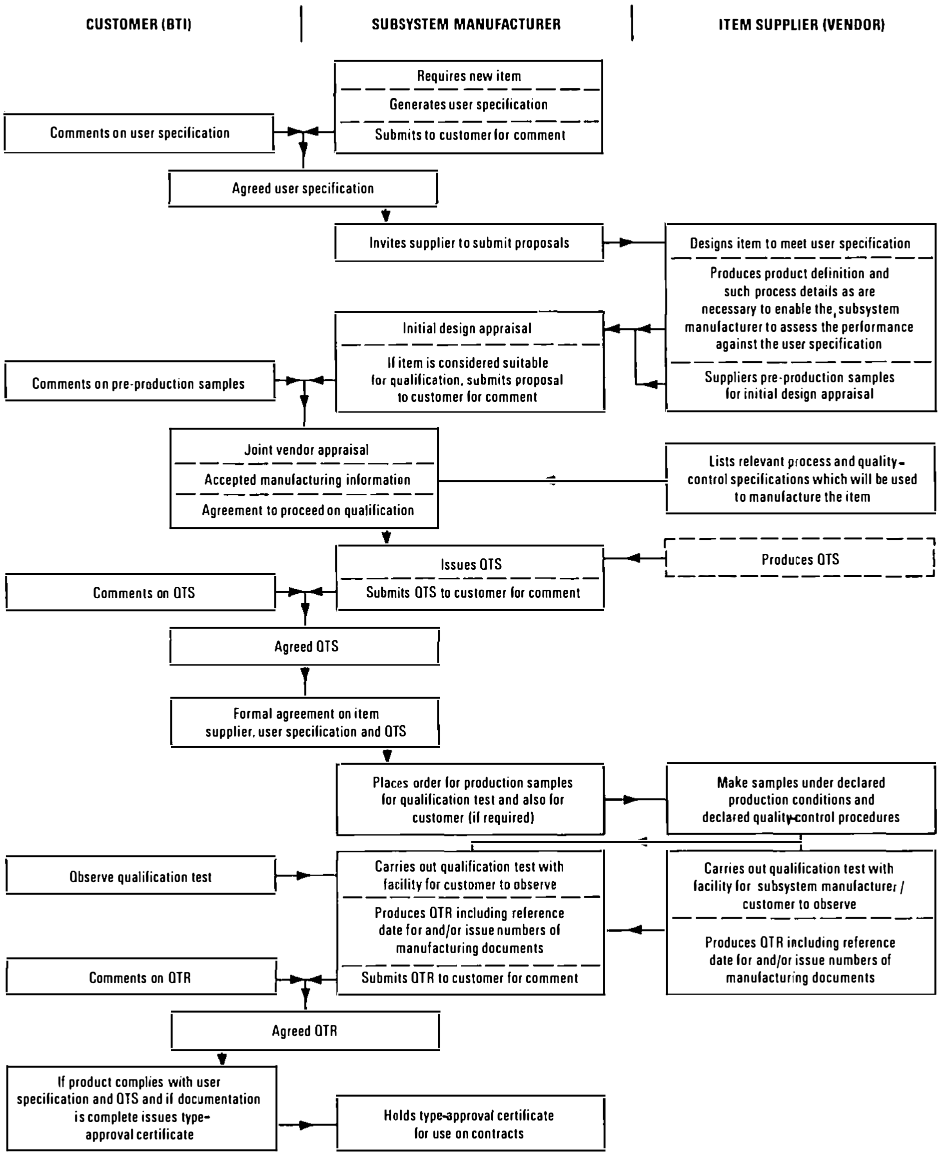
† 1 FIT = 1 fault in 10^9 hours.

* Cumulative hazard is the proportion of devices failing in a given period of time.



QTR: Qualification test report QTS: Qualification test specification

Fig. 3—Flow chart of typical type-approval procedure

The BT team usually comprises operational, technical and quality-assurance advisers. The contractor usually has a similar complement. Auditing of components manufactured by the contractor is done by the BT team only.

Briefly, the audits, at the place of manufacture, consist of an initial scrutiny of the relevant process documents and inspection documents guided by an overall flow diagram which details all the processing steps and inspection stop points.

This is normally followed by a visit to the plant, where all or selected processes are examined. A close check is made to verify that these processes are carried out strictly in accordance with the agreed documentation. Any discrepancies are noted at this stage with requests for explanation.

After the plant visit, there is generally a discussion of the points arising from the plant visit and the earlier examination of the documentation. Any action points are identified and time-scales for their completion are suggested.

Finally, the audit team produces signed audit reports, wherein permission is formally given for the manufacture of qualification samples etc., subject to the clearance of any outstanding remedial actions.

QUALIFICATION TESTING OF COMPONENTS

A qualification test specification (QTS) is produced for any component to be qualified. All the tests outlined in the QTS are based on the relevant British Standard (for example, BS 2011) wherever possible. The prime requirement is that any component submitted for qualification must have been made by the normal manufacturing operation of the contractor/supplier.

Generally, the components being qualified are split into five or six groups with a minimum number in each group. Each group deals with one or more different tests such as temperature cycling, bump and vibration, damp heat, solderability, endurance etc. that are designed to show that the components can withstand fairly severe conditions without detriment to their mechanical or electrical properties. Furthermore, a number of components undergo accelerated life tests to determine their long-term reliability. However, these life tests are not part of the qualification *per se*.

Upon completion of the qualification programme, a qualification test report (QTR) is produced giving all the test conditions and results, together with the conclusion on the suitability of the component in question.

If the report is satisfactory, the contractor may then apply for formal type approval from BTI. A type-approval certificate is then issued by BT when it is satisfied that, in addition to the QTR, all the documentation is correct regarding issues and updates etc.

REGENERATOR MODULE QUALIFICATION

As for any other item to be qualified, a QTS for the regenerator-pair modules is produced by the contractor and agreed with BT. Because regenerator pairs are complex and very expensive items, compared to individual components, the number of regenerator pairs to be used for qualification is limited to a small number, say three, of which two undergo the rigourous tests and the remainder kept as a control.

The regenerator pairs are made and tested by manufacturing personnel following normal documented manufacturing processes. The individual units are sealed after a standard high-temperature production bake-out, and fully leak tested. A QTR is issued, as for the components, upon completion of the test programme. If the report is satisfactory, that is, the regenerator pairs have fulfilled all the requirements of the agreed QTS, the contractor may then apply for type approval from BT in accordance with the type-approval specification described earlier.

SCREENING OF COMPONENTS

All submarine components require exacting manufacturing standards. However, in the manufacture of these components, material and processing abberations can occur. It is therefore essential that any flawed component which might fail early in its life is removed; this is accomplished by effective screening.

Screening demands that flaw-free devices are accepted and flawed devices rejected. Representative screening processes require operation of the device at higher temperature, currents and/or voltages for a limited time. In designing screens, the effectiveness of the screen must be evident and this is usually made apparent by the inclusion of parametric, mechanical and physical testing. By virtue of such screening, some effective life is extracted from the good components usually at the burn-in[3] included in the screen.

Typical burn-in conditions in the manufacture of components are given in Table 2.

TABLE 2

Typical Burn-In Conditions Used in Component Manufacture

Device	Duration (hours)	Temperature (°C)	Remarks
Integrated circuits	96	160	Biassed
PIN diode	96	150	Biassed (part of optical receiver)
Optical receiver	64	100	Biassed

HERMETICITY

Those components demanding an enclosed and controlled working ambient are hermetically sealed, and stages in the screen must allow for the demonstration of hermeticity. The method of enclosure construction and size usually determine the expected leak rates for the component. Hermeticity of semiconductor components is covered elsewhere[4, 5]. Current requirements demand a leak rate better than 1×10^{-8} bar cm^3/s.

CONCLUSIONS

The authors of this article have deliberately not presented a rigorous mathematical treatment of the reliability aspects of submerged repeatered systems and their components. Instead, an overview of this reliability, together with some typical current values of demonstrable failure rates, has been given. In addition, a substantial part of the article has concentrated on the way BTI deals with the qualification and type approval of components and units for submerged repeaters. Engineering audits of the manufacturers of various components have been found of great value in pursuing and achieving highly reliable products. The audits force the manufacturers to exercise greater discipline in the production of their wares, and they afford the auditors a better understanding of the inherent difficulties faced by the suppliers of submarine cable systems.

With the introduction of new components for modern digital optical systems, the demanding reliability requirements cannot be relaxed and the procedures outlined must be followed to ensure that modern components continue to maintain the high performance demanded for submarine systems.

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Biographies

Odvar Petterson was born in Norway and educated in Oslo and, later, Stockholm, where he graduated, in 1952, in Radio and Telecommunications at the Stockholm Technical Institute. He worked as a Research Assistant at the Royal Institute of Technology in Stockholm until 1956, when he joined Submarine Cables Ltd. at Greenwich. There he was employed as a development engineer, initially working on the design and development of high-reliability components and circuits for submerged repeaters, and later engaged in the laying and commissioning of submarine cable systems. He joined BT as an open entrant Assistant Executive Engineer in 1971 in the Submarine Cable Division, where he worked on the maintenance of transatlantic systems until his transfer to the Commissioning Group in 1973 with the tasks of documentation approval for submarine cable systems, and oversight of their manufacture, installation and commissioning. He became a temporary Executive Engineer (EE) in 1979 when working in the North Sea Area Planning Group, whence he joined the System Engineering Group, in 1980, where he was promoted to EE in 1983. His present duties include the type approval of components for optical/digital submerged repeaters and the monitoring of research and development work.

John Tew joined the Wireless Experimental Branch at Dollis Hill in 1954 as a Youth-in-Training. Since 1962, apart from a short period in personnel, he has been associated with the characterisation, testing and manufacture of high-reliability devices for submarine applications. He is currently Head of the ECL 40 Development and VLSI Production Control Section with the Microelectronics Design and Applications Division within Technology Executive.

Repeater Design Requirements

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The design requirements of optical submarine repeaters extend well beyond those dictated by the transmission requirements, fundamental though these are. The supervisory systems on first generation optical systems are much more complex than those found on later analogue systems. The repeater internal unit must be designed with a view to good heat dissipation as well as robustness. The power supply configuration must take into account, amongst other things, the sensitivity of some opto-electronic components to voltage surges. Reliability continues to be a prime consideration. This article discusses all these factors.

INTRODUCTION

The feasibility of using submerged repeaters in submarine telephone cables was first established in 1943 when an experimental repeater was laid in a cable between the Isle of Man and mainland Britain. In the succeeding 40 years, much experience has been built up in the problems of repeater design, and the technology has advanced, allowing a hundredfold increase in cable capacity with an associated reduction in circuit cost. While each new generation of system has built upon the experience of the preceding ones, new and unexpected phenomena have continued to emerge, requiring repeater designers to maintain due prudence in their approach.

The introduction of optical technology into submarine cables builds upon the previous experience with coaxial cables. However, the change to digital transmission using optical-fibre techniques represents a major jump in technology, and consequently introduces a new set of requirements for the repeater designer[1]. Historically, submarine systems have lagged behind land-based systems in the introduction of new technology, since reliability requirements have dictated a conservative approach. However, the development of optical technology has taken place in broadly similar time-scales for land and submarine systems, and this has required a greater than usual degree of caution on the part of designers of submarine systems in using land-system experience. The inaccessibility of submarine systems also means that their design requirements differ considerably from those of land systems, primarily in the areas of reliability and ability to locate faults, etc.

The factors to be considered by the designer of optical submarine repeaters may be grouped under the following headings:

Transmission Performance
Supervisory Subsystem
Power Supply
Mechanical Construction
Reliability

This article outlines the design requirements under these headings.

TRANSMISSION PERFORMANCE

The block diagram of a typical optical regenerator for first-generation systems is shown in Fig. 1.

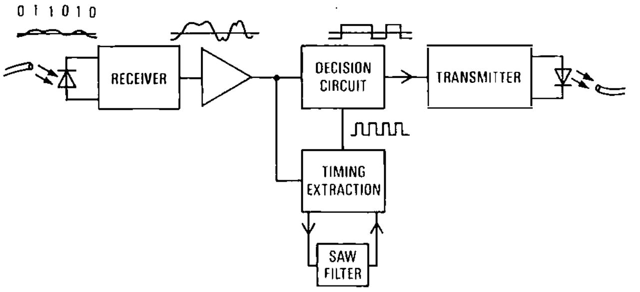

Fig. 1—Block diagram of regenerator

Error Ratio, Design Penalty and Margins

The design of optical repeaters is, as might be expected, a compromise. In this case it is between repeater spacing and error ratio. The target is clearly to maximise the spacing whilst ensuring as far as possible that the end-of-life error ratio is acceptable. A 'power budget' is drawn up which might typically read (in abbreviated form) as follows:

Laser launch power (into fibre tail)	−3 dBm
Receiver sensitivity	−34 dBm
	31 dB
Less tolerances, known penalties, etc.	4 dB
Nett path loss capability	27 dB

allocated to

Fibre loss (including splices)	18 dB
Repair allowance	2 dB
Ageing allowance	4 dB
Operating margin at end of life	3 dB

So far as the system designer is concerned, the importance of error ratio is related to its affects on particular customer services. The relevant CCITT* Recommendation[2] is concerned with error performance objectives for an international ISDN hypothetical reference connection (HRX) at 64 kbit/s. Limits are laid down for the percentage of 1-minute intervals with an error ratio greater than 10^{-6} ('degraded minutes'), the percentage of 1-second intervals with an error ratio greater than 10^{-3} ('severely errored

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† Technology Applications Department, British Telecom Development and Procurement

* CCITT—International Telegraph and Telephone Consultative Committee

seconds'), and the percentage of 1-second intervals to have any errors at all ('errored seconds'). A full discussion of this topic can be found in Reference 3.

Repeater designers are likely to have some difficulty relating these requirements to their own work. The testing of regenerator electrical noise performance is almost always carried out by using Gaussian noise, and this leads to a Poisson-type distribution of errors in time. (The Poisson distribution is the one which also applies to telephone call attempts at a particular exchange.) In the testing of optical repeaters, errors are generated by the noise in the receiver: the characteristics of this noise varies according to receiver type.

Regenerators are designed with tolerances and ageing margins which give unmeasurably low error ratios at the start of their lives. This results from the steepness of the error ratio/signal-to-noise (S/N) ratio curve for error ratios below 10^{-12} (see Fig. 2). For example, a repeater with a 6 dB (electrical) (that is, 3 dB optical) margin against a 10^{-12} error ratio would have an error ratio of 10^{-33}, a figure which must be set in the context that a 300 Mbit/s regenerator transmits about 10^{18} bits during a 25-year lifespan. Studies of errors in installed terrestrial systems have shown non-Poisson distributions, tending to occur in bursts[4]. Generally speaking, the causes of these errors must lie outside the repeaters, and discussion of them thus falls outside the scope of this article.

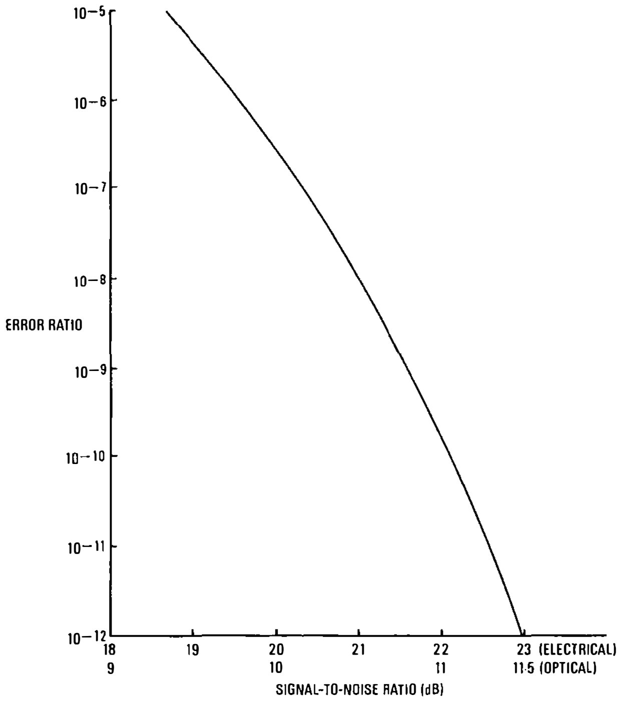


Fig. 2—Error ratio versus S/N ratio

The repeater designer's task, then, is to guard against the effects of ageing on various components which might reduce the margin against an acceptable error ratio. An acceptable error ratio for a regenerator section would be one that would give an overall error ratio on a long-haul system of 10^{-9}. In a system with 200 repeaters, this might be around 10^{-12} per section when an allowance for terminal equipment has been made. Factors which can cause degradation of noise performance during system life include: change in the decision threshold, change of sampling epoch, ageing of laser resulting in power loss or extinction ratio decrease, and changes in the optical receiver element (PIN diode or avalanche photodiode (APD)).

Taking these in order:

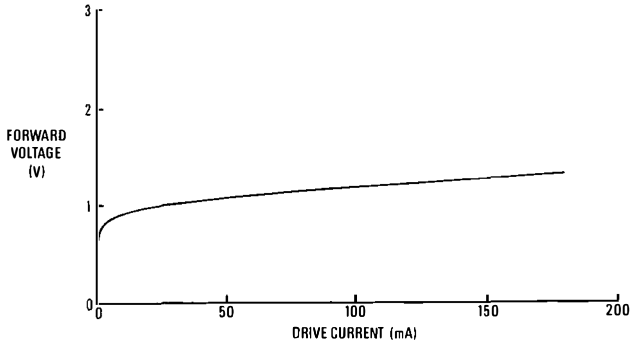
The decision as to whether a regenerated bit is a ONE or a ZERO (speaking with reference to a 2-level system) is made with respect to a fixed threshold between the two levels. Changes in this threshold voltage can be minimised by the use of balanced regenerator circuitry. At the speeds used in first-generation submarine systems, emitter-coupled logic (ECL) is universally used in the repeaters. This readily lends itself to balanced operation, the only penalty being a small increase in power consumption.

The time delay through the timing recovery path can vary with time and temperature, and the variation can be different from that of the parallel data path (see Fig. 1). The time delay through a surface-acoustic wave (SAW) filter is independent of other parameters, but in general it is much larger than the delay of, say, a tank circuit. Therefore the timing epoch will be relatively sensitive to changes of clock frequency and changes in SAW parameters with temperature and age. There are two ways of compensating for these effects in the repeater:

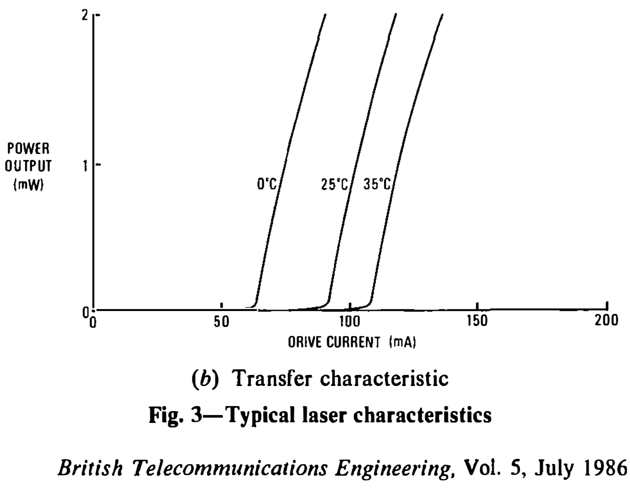
(*a*) use of a SAW with a temperature coefficient which opposes that of the retiming amplifier, and
(*b*) adaptive timing epoch adjustment, in which feedback from the output of the decision bistable can be used to change the phase of the recovered clock.

The latter is more secure as it compensates for frequency shift, temperature and ageing effects (whereas the former compensates for temperature only), but so far it has not found favour in submerged repeaters because of the extra circuitry and power consumption it requires.

From the driving viewpoint, the laser behaves very much like a semiconductor diode. The characteristics of a typical laser are shown in Fig. 3. Its threshold current (the current



(*a*) Driving point characteristic



(*b*) Transfer characteristic

Fig. 3—Typical laser characteristics

corresponding to the knee of the transfer characteristic) will depend on temperature and age. It is important, for reliability reasons, to control the mean power output of the laser: if this grows too large, then the device lifetime will be shortened; and if it becomes too low, then the performance of the next regenerator in the chain may be put in jeopardy. Also, it is important to switch the laser on from an operating point close to the threshold. If the device is turned off too far, the turn-on delay may be excessive, and too dependent on the data pattern; that is, the phenomenon known as *patterning*. If it is not turned off sufficiently, the extinction ratio (the ratio of light output when ON to output when OFF) reduces, reducing in turn the signal level at the following regenerator[5].

Thus, two control systems may be needed in the laser drive electronics: one to maintain constant mean power, and one to ensure that zeros in the data switch the laser to a point consistently close to the threshold. In both cases, the laser output is usually monitored by feeding light from the back facet to a photodiode. The latter control can be effected by a small amount ($\approx 1\%$) of amplitude modulation of the zeros of the data feeding the laser, at a frequency at which there is insignificant power in the data. If this cannot be achieved, as for example with 24B1P code which has strong components at all frequencies down to DC, control can still be achieved at the expense of some extra circuit complication.

Jitter and Timing Circuit Design

Jitter is defined[6] as *short-term variations of the significant instants of a digital signal from their ideal positions in time.* Jitter can be considered as phase modulation of the underlying timing of a digital signal. For a discussion of the importance of jitter control, the reader is referred to an article by Kearsey and McLintock[4]. As with error ratio, the importance of jitter control lies in the possible effects on the end-users of particular services, and the repeater designer's approach will probably be simply to minimise jitter, in particular, the systematic component.

Jitter in optical repeaters arises from five main causes: intersymbol interference (ISI) due to imperfect channel equalisation (this is unlikely, given the very large bandwidth of the actual fibre); imperfections of the timing recovery circuit (mistuned SAW filter, amplitude-to-phase conversion in the retiming amplifier); crosstalk between circuits in a regenerator, or between regenerators in a repeater; ageing; and laser patterning. Of these, the ones causing systematic jitter are to be taken the most seriously; that is, ISI, amplitude-to-phase conversion and laser patterning. This is because the upper bound of systematic jitter accumulation is proportional to the square root of the number of regenerators, whereas the upper bound of random jitter accumulation is proportional to the fourth root[7].

Laser patterning is caused when the turn-on delay becomes pattern-dependent. A remedy for this has been discussed above. So far as ISI is concerned, then the limiting factor in channel bandwidth is usually the optical receiver. It is not difficult to produce a very low value of ISI with simple equalisers.

Amplitude-to-phase conversion in the retiming amplifier causes jitter because the SAW filter output varies with the density of transitions in the data message in any given period. Thus, the jitter is influenced by both the line code and the SAW filter bandwidth. In practical designs, the second of these is usually determined from the first. Amplitude-to-phase conversion is not an obvious amplifier design parameter, but sometimes the retiming amplifier design can be refined to minimise the variation in the region of interest.

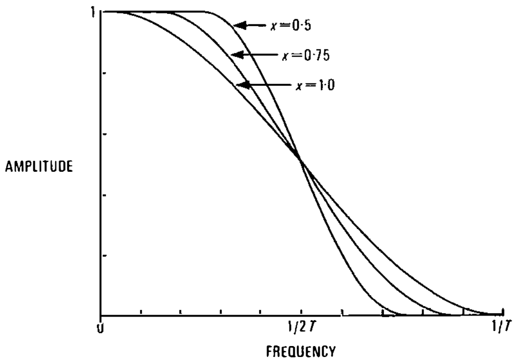
Alignment Jitter

In a chain of identical regenerators, the accumulation of jitter should have only a minimal effect on the error performance of the individual regenerators. This is because the received data and the recovered clock are varying in a virtually identical way in this situation. However, if a SAW should become mistuned, or if two systems with markedly different SAW characteristics are joined together, then at the first regenerator, the clock and data at the decision bistable may have sufficient relative jitter to affect the error performance of the repeater by reducing the design margins. This phenomenon is known as *alignment jitter*[8]. In the case of TAT-8, where the three segments are being supplied by different manufacturers, efforts have been made to minimise this effect by ensuring that SAWs of the same nominal bandwidth are used throughout.

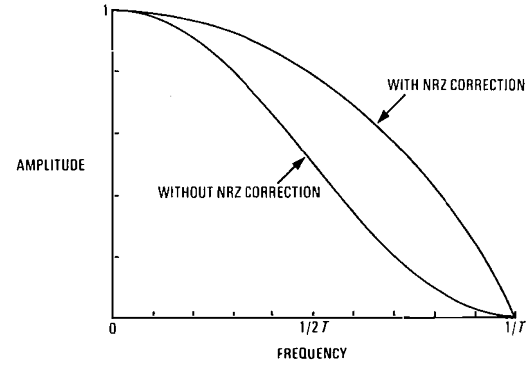
Channel Equalisation

The optical-fibre link has a very large inherent bandwidth, but this is not matched by the optical receiver. Bandlimiting is applied by an equaliser following the receiver, which shapes the channel to minimise pulse distortion and reduce the noise power at the decision circuit. Sufficient conditions for data transmission over a band-limited channel were derived in 1928 by Nyquist[9]. His analysis is for non-return-to-zero (NRZ) pulses, but is easily extended to the return-to-zero (RZ) case. The 'Nyquist channel' has flat group delay and skew amplitude symmetry about the frequency $f = 1/2T$, where T is the unit interval.

The Nyquist criteria are not necessary conditions for data transmission and, in practice, an equaliser may well be adjusted for a satisfactory channel time response rather than for skew-symmetric amplitude response and flat group delay. Even so, discussions of this topic generally assume a raised-cosine channel response with the NRZ adjustment (see Fig. 4), as this is a fairly good approximation to reality and it is mathematically tractable. The raised-cosine amplitude



(*a*) Raised-cosine channels with various roll-off rates



(*b*) $x = 1$, with and without NRZ correction

Fig. 4—Data transmission amplitude response

it is mathematically tractable. The raised-cosine amplitude response is expressed:

$$G(f) = 1 \qquad 0<|f|<W(1-x)$$

$$G(f) = 0{\cdot}5\left\{1-\frac{\sin\pi\,(|f|-W)}{2xW}\right\} \quad W(1-x)<|f|<W(1+x)$$

where x is the roll-off factor and $W = 1/2T$.

NRZ adjustment: $\hat{G}(f) = G(f)/\mathrm{sinc}\ (\pi f T)$.

The roll-off factor x is arbitrary within limits—a sharp roll-off (small value of x) presents practical difficulties. In practice, a gradual roll-off ($0{\cdot}75 < x < 1$) is the norm on optical systems, and this means four things:

(*a*) departure from the raised-cosine ideal can be fairly severe before appreciable distortion occurs,

(*b*) the group-delay variation is small and does not need to be separately equalised,

(*c*) the channel noise bandwidth is minimised, and

(*d*) the regenerator is more jitter tolerant.

The Effect of Electro-Optics

It may be instructive to regard the laser (coupled to its cavity) as a keyed oscillator, running at optical frequency (≈200 THz). Like some electronic oscillators, the laser can oscillate in any one of several modes. In the few nanoseconds following switch-on, certain modes will grow whilst others decay. Successive pulses may produce different patterns. This is relatively harmless at 1·3 μm where the fibre dispersion (that is, the variation of propagation velocity with wavelength, which is akin to group-delay) is negligible, but at 1·5 μm, it is necessary to use a truly monochromatic laser such as the distributed feedback (DFB) type[10], or fibre in which the dispersion zero has been shifted in wavelength[11].

SUPERVISORY SUBSYSTEM

The following section describes the factors to be taken into account in the design of the supervisory subsystem of optical submarine repeaters. The reader is referred to a companion article[12] for a description of how these requirements have been met in the design of a typical system.

Purpose and General Requirements

The prime function of the supervisory subsystem of a submarine cable system is that it should allow a faulty repeater requiring replacement to be identified with the least possible ambiguity; that is, it should minimise the risk of a cable ship being sent to recover a repeater which subsequently turns out not to be the one that was faulty. Since in this case a system outage is inevitable, it is acceptable for this prime requirement to be met on an out-of-service basis.

The second requirement is for the identification of incipient faults in situations where there is scope for taking steps to minimise the disruption to traffic. In this case, in-service facilities have an advantage, since the system may still be within specification though degrading (with, say, the probability of error (P_e) = 10^{-9}), or it may be acceptable for telephony if not for data ($P_e = 10^{-4}$). The steps to be taken may involve:

(*a*) a planned repair operation, in which case traffic can be maintained up to the moment of commencing a repair, a particular advantage on long systems where the passage of the ship may take several days; or

(*b*) switching in of a redundant subsystem or component if these have been incorporated in the design.

A third use of the supervisory system (which may overlap with the second) is a final check on section margin at the time of installation or following a repair. The steepness of the P_e versus S/N ratio curve on digital optical systems (Fig. 2) is such that a reduction in margin due to poor splices etc. will not show up on overall performance although it may well affect system life by eroding the margin against ageing. It is therefore useful to check at the time of installation or repair that the full required ageing margin exists. This requirement can be met out-of-service, since it is only required following an outage.

If the system design allows, or depends on, the use of redundant stand-by subsystems for reliability purposes, then the remedial action required may involve a remotely-controlled switching operation, which can be considered to be the fourth possible requirement. If more than a very small number of switching operations during the system life are contemplated, then this requirement should be met in-service.

Characteristics

Supervisory subsystem design must allow the first of the above requirements, and ideally some or all of the others, to be implemented in a manner which exhibits the following characteristics:

(*a*) *Security* The prime requirement of failure location must be met under any possible fault condition (provided that the cable can be powered).

(*b*) *Robustness* Failure of a supervisory unit in one repeater should only result in a small increase in ambiguity (that is, location to the nearest section may be degraded to location to two adjacent sections).

(*c*) *Fail-Safe* The subsystem should present the minimum hazard to the main transmission path.

Bearing these characteristics in mind, the designer must choose the facilities to be provided as appropriate tools to meet the four requirements detailed earlier.

Facilities

Table 1 shows typical facilities provided on first-generation optical-fibre submarine systems and brief details of these are given below. However, these facilities are simply selected ways of meeting the requirements. Later system designs may allow these requirements to be met with simpler sets of facilities, depending upon the fibre configuration required.

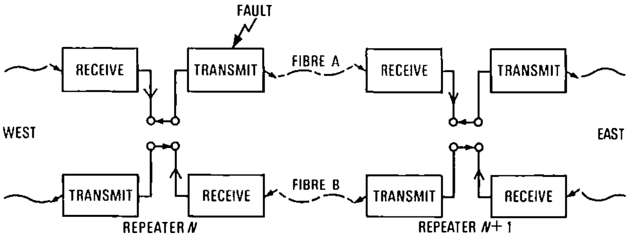
TABLE 1

Typical Facilities

Requirement	Facilities
Location of failed repeater (Out-of-service)	Loop-back of transmission path
Location of incipient failure (In-service)	Status of transmitter—laser health Detection of error events
Margin check (Out-of-service)	Received light level or section margin
Implementation of redundancy (Out-of-service)	Remote laser change-over Remote path switching

Loop-Back

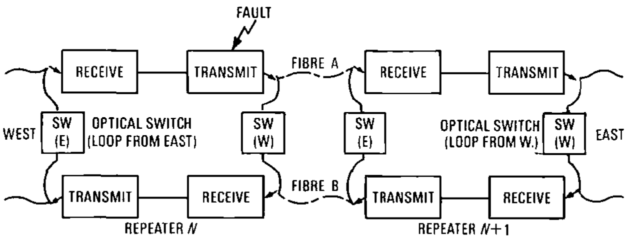
Loop-back of the main transmission path can be imple-



LOOP-BACK TRUTH TABLE FOR FAULT IN TRANSMITTER A_N

Loop from / Loop at	W	E
N	Yes	No
N+1	No	Yes

(*a*) Electrical loop-back



SW : OPTICAL SWITCH

LOOP-BACK TRUTH TABLE FOR FAULT IN TRANSMITTER A_N

Loop from / Loop at	W	E
N	No	No
N+1	No	Yes

(*b*) Optical loop-back

Fig. 5—Loop-back arrangements

mented at either electrical or optical points on a fibre pair as shown in Fig. 5.

Electrical loop-back in both directions at a common point in the regenerator is simple to implement, but can be less precise than optical loop-back at the two extremes of the regenerator. In the example shown, the truth tables apply for a fault in transmitter A_N; the use of electrical loop-back alone could not distinguish between this condition and a fault in receiver A_{N+1}, whereas optical loop-back would give different truth-tables for the two conditions. In practice, the relative merits of the two techniques are not quite so clear cut. If it is used in conjunction with other facilities such as laser health monitoring, the ambiguity of electrical loop-back can be somewhat reduced. Conversely, optical loop-back can require more complicated optical couplers etc. which rather reduce its inherent attractiveness. Either technique can be satisfactory provided due attention is given to the requirements outlined above.

Transmitter Health

Life-test data indicates that the dominant ageing effect in 1·3 μm InGaAsP lasers is an increase in threshold current. Assuming that the transmitter includes a feed-back loop to adjust the bias current in order to maintain the mean optical power, a measure of the bias current will give an indication of laser health. However, monitoring of this parameter alone is not entirely foolproof. Depending upon the design of the transmitter, the monitor may not respond to other possible failure mechanisms such as changes in laser slope efficiency, failure of modulator circuit or changes in laser-fibre coupling efficiency (if rear-facet monitoring is used). However, it is a reasonable compromise between usefulness and simplicity which is considered adequate in the absence of any firm evidence to the contrary.

Error Events

Precise measurements of error performance may be performed on an out-of-service basis using loop-back. The additional facility of detecting a source of errors in-service is therefore required only to allow planning of a repair or identifying which redundant subsystem or component should be substituted (second requirement above). While erosion of system margin could lead to an increase in mean error ratio, the more serious problem could arise from intermittent error bursts. On a long system, these could well take a long time to locate, hence the advantage of an in-service facility. Ideally, the error-event detector, if provided, will be able to identify the source of error bursts even in the presence of a low-level (acceptable) background error-ratio (say $P_e = 10^{-10}$).

Received Light Level or Margin

This requirement may be met either through measurement of signal levels at, or following, the receiver, or by measuring margin against errors at the decision circuit by using, for example, a pseudo-error technique[13].

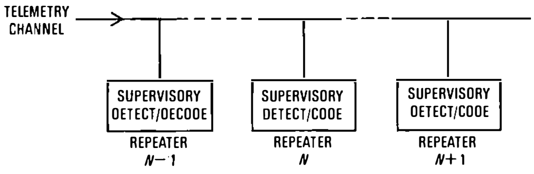
Remote Switching

Switching may take place in either the electrical or optical paths, and be achieved by using either mechanical or solid-state devices. The choice is governed by the technology available to the designer.

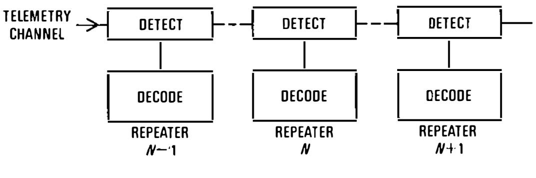
Telemetry Channels

Almost all of the facilities listed above require a telemetry channel between the terminal and a repeater. Such a channel may be carried by frequency or phase modulation of the signal clock, use of special patterns with particular spectral or parity characteristics, etc. Whatever bearer is used, the telemetry system must exhibit the above-mentioned three characteristics; that is, it must be secure, robust and fail-safe. An example of the way in which this affects the design can be seen from the topology of the telemetry system. Fig. 6 shows two possible techniques.

Parallel addressing (Fig. 6(*a*)) has the advantage that one or more supervisory units can fail without this affecting the operation of the remaining ones. It is therefore an inherently more robust arrangement than serial addressing (Fig. 6(*b*)), and so is to be preferred.



(*a*) Parallel-addressed supervisory channel



(*b*) Serial-addressed supervisory channel

Fig. 6—Telemetry channel topology

POWER SUPPLY CONFIGURATIONS

As with analogue coaxial cables, the technique adopted as standard on optical submarine systems is constant-current series DC power-feeding, using the sea as the return path (Fig. 7).

This technique is simple in concept and allows systems to be unaffected by the induced voltages which occur during magnetic storms[14]. The disadvantage is the high-voltages near the ends of the cable. In the event of a cable fault, the charge stored in the cable capacitance escapes to earth giving rise to high surge currents. Repeaters must include surge protection circuits (generally comprising Zener diodes and gas-discharge tubes) to allow these high surge currents to by-pass the regenerator circuits without giving rise to damaging voltage spikes[15].

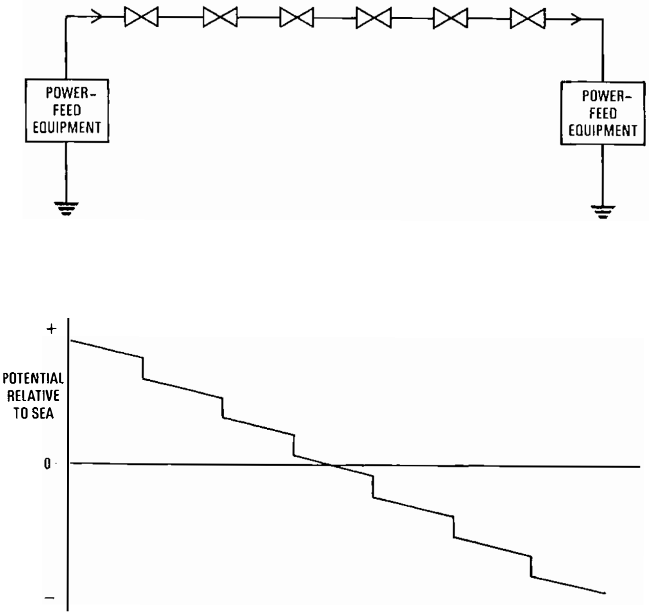


Fig. 7—Constant-current series DC power feeding

For a given repeater power consumption P_R (typically 40 W), and cable conductor unit resistance R (0·75 Ω/km), it can readily be shown that the lowest overall system voltage is achieved when a line current is selected which causes the voltage drop in a cable section to equal that in a repeater.

Thus, if d is the section length,

$$I_{opt}Rd = \frac{P_R}{I_{opt}}$$

$$\therefore \quad I_{opt} = \sqrt{\left(\frac{P_R}{Rd}\right)}$$

The various regenerator circuits in a repeater housing should ideally be arranged in such a manner that the required line current is not too far from this optimum value. The use of high-speed ECL integrated circuits means that most circuits require low voltage and comparatively high current. To restrict the cable current to somewhere near to the optimum, therefore, requires some series-stacking of the circuits from the power-feed viewpoint. Typical configurations for GO and RETURN regenerators in a repeater of a 4-fibre system are

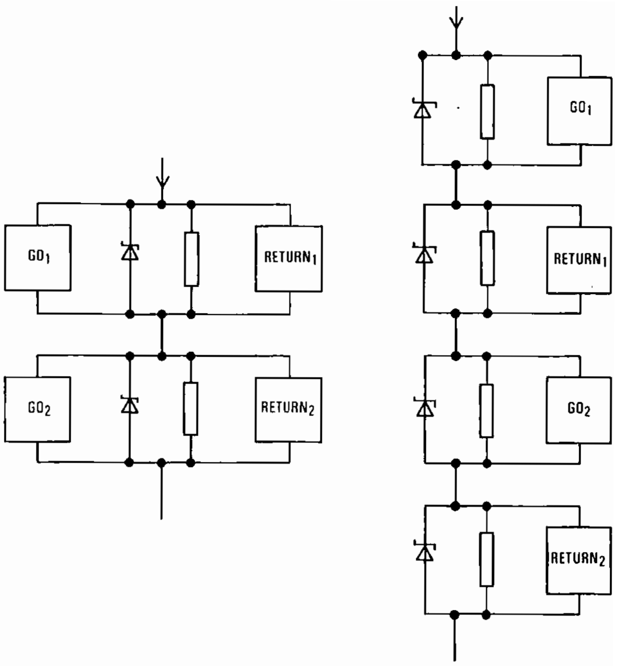


Fig. 8—Typical configuration for powering four regenerators in a repeater housing

shown in Fig. 8. Considerable care must be taken in the practical implementation to avoid transmission penalties due to cross-talk paths.

An additional factor to be allowed for in the design of the power circuit configuration is the low-frequency electrical transmission performance of the power path. The electrical path along the cable and through the repeaters is used in the location of cable faults. The techniques used are mentioned in another article[16] and involve DC testing and transmission of low-frequency pulses. These impact on the repeater design by implying the following requirements for the power path:

(*a*) a known and stable constant resistance characteristic over a range of low line currents (say −10 to +50 mA). (this assists in the use of DC tests), and

(*b*) a low through loss for frequencies up to 30 kHz, (pulse echo and impedance/frequency characteristic measurements use this frequency range).

MECHANICAL CONSTRUCTION

The unit housing the repeater circuitry is basically a shock-resistant watertight box, but, in optical systems, there are other design considerations. The temperature of the laser must be limited if its life is not to be shortened, and, in general, the housing and internal unit must be designed for the best possible heat transfer from all active components for reliability reasons. At the same time, the repeater circuitry must be insulated from the sea, and the insulation must tolerate the full system supply voltage for 25 years. Devices such as Peltier coolers are not yet qualified for submarine use and are not used on first-generation systems. Fortunately, polyethylene and alumina, two traditional insulants, prove to have quite adequate thermal properties in designs where careful attention has been paid to the internal unit layout[17].

RELIABILITY

The inaccessibility of submerged plant means that any failure results in a very high cost to the operating administrations. This arises from the cost of providing service by alternative routeings during the outage, the mobilisation of a repair ship, and the provision of replacement plant (and additional plant in the case of a deep-water repair). For this reason, extreme care must be taken to ensure that the possibility of repeater failure is minimised. Typical systems have a target reliability of only two or three failures over system life. Associated with this is the design life of submarine cables. The high cost of manufacturing and installing reliable cables means that it is appropriate to aim at a lifetime of 25 years. Experience with analogue systems shows that this is a reasonable target; the Aberdeen–Bergen cable was taken out of service recently, after 28 years of use. There are some grounds for reducing the target life since technology is moving so fast that systems more than 15 years old are beginning to be regarded as obsolescent. However, any reduction would give only a minute saving in system cost, because components would still need to be of the highest quality. Any saving would arise only from a very slight reduction in the required testing. The provision of redundant components or complete regenerator and fibre sections can sometimes provide advantages in easing the extent of the reliability proving required for components, but care must be taken to ensure that any required switching elements do not introduce additional hazards. The subject of component reliability is covered in detail in another article in this issue[18].

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Biographies

Paul Dawson passed the IEE Part III examination in 1969, and obtained the M.Sc. degree in Electronics from the University of Southampton in 1972. Between spells of academic study, he spent periods with Pye TMC and the Plessey Company. He joined BTRL in 1972 to work on speech-band data modems and digital transmission in the local network. After a period heading a group running Pathfinder, the first British public stored-programme control telephone exchange, he joined the Submarine Systems Research Division in 1981 to head a group primarily concerned with the development of optical-fibre submarine repeaters.

Ken Fitchew received the B.Sc. degree in Electrical Engineering from the University of Bristol in 1970. He joined BTRL in that year and worked in the repeaters and systems section of the Submarine Cable Division. Since 1979, he has been a Head of Group involved in the co-ordination of the development of optical-fibre systems.

Cable-to-Repeater Connection and Repeater Mechanical Design for Submarine Optical-Fibre Cable Systems

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UDC 621.315.28 : 621.391.63

Submarine optical-fibre cable technology has placed severe demands upon the design of cable and repeaters. This is also true of the interconnection device between the cable and repeaters. The cable design is more complex and the silica glass transmission medium comparatively fragile. Penetration of the power feed and individual fibres via glands into the repeater bulkhead poses new problems. The termination between the cable and repeater must allow for tensile and bending strains of the fibre as well as that of the cable-to-repeater coupling. Fully flexible couplings with a large number of metallic components necessitates a review of the corrosion liabilities.

INTRODUCTION

The design life for submarine optical-fibre cable systems is normally 25 years. This places stringent requirements on the reliability of not only the transmission medium, but also the mechanical properties of the cable structure, the repeater components and the housing.

The importance of the coupling to the repeater housing must therefore not be overlooked. Thus there are strict requirements regarding the engineering of all the components that make up the termination system, and an extensive range of quality-assurance tests.

The repeater housing is normally specified to withstand a 50 *g* shock load and maximum deep water depth to a pressure of say 77 MPa, and maintains absolute watertightness and low humidity. The established technology of the coaxial pigtail from the sea into the sealed gland chamber must be developed further for optical systems. There is now a requirement for a very-low hydrogen leakage rate from the sea environment through to the opto-electronic components in the housing. Also, the optical transmission loss of the fibre from the sea cable to the regenerator components must be kept within strictly controlled limits, ideally no worse than the loss of a good splice, say 0·1 dB for a 1·3 μm system.

It is readily realised that, for the practical purposes of cable attachment, in the factory or during repair, the optical cable must be terminated in a pressure-resistant chamber where power-feed and transmission-fibre splicing can be carried out. Access to this splice chamber is required so that the regenerator, completely sealed in the clean room conditions of manufacture, is not affected by any subsequent operation. During the life of the termination, any moisture that might appear in the sea cable, possibly owing to damage, must not be allowed to progress into the pressure housing. The gland splicing chamber should be regarded as a flexibility point for each repair. Thus it can be seen that an individual power-feed gland, as well as separate transmission-fibre glands, are required. This represents two new areas of technological development for optical systems.

REPEATER HOUSING

Pressure-resisting housings for repeaters now tend to be of a universal design (Figs. 1 and 2) for both shallow-water and deep-water systems. Traditionally, they must have a maximum working depth of approximately 6500 m, equivalent to a sea pressure of 65 MPa (4·2 tons per square inch), be able to withstand shock loads of 50 *g*, be absolutely watertight and maintain the internal environment with a low humidity. With the development of optics, there is now an additional requirement for a very low hydrogen leakage rate into the opto-electronic assembly from the sea environment.

The main structual component of the housing is the tubular sea case into which the opto-electronic units are enclosed. The case is sealed by removable high-tensile alloy steel bulkheads at each end.

Various metals are used for the sea case. It is also generally desirable to have a system to prevent contact between sea water and the steel surfaces of the repeater housing to eliminate metal wastage and hydrogen generation through galvanic corrosion and magneto hydrodynamic effects.

A typical material used for the housing is a nickel-chrome molybdenum alloy, which is coated with an epoxy coal

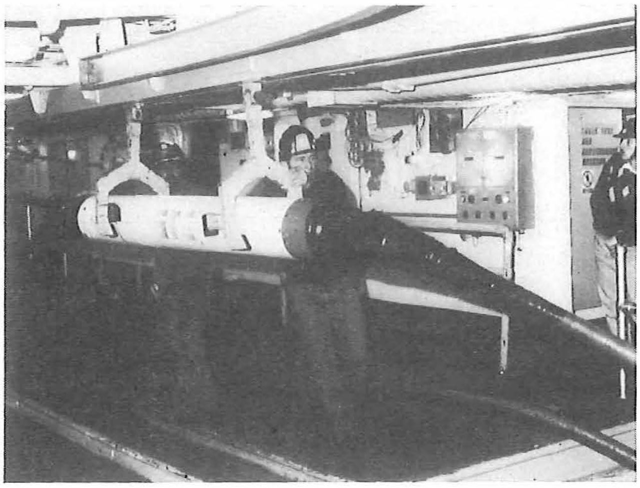

Fig. 1—UK–Belgium No. 5 repeater aboard *CS Alert* prior to being laid

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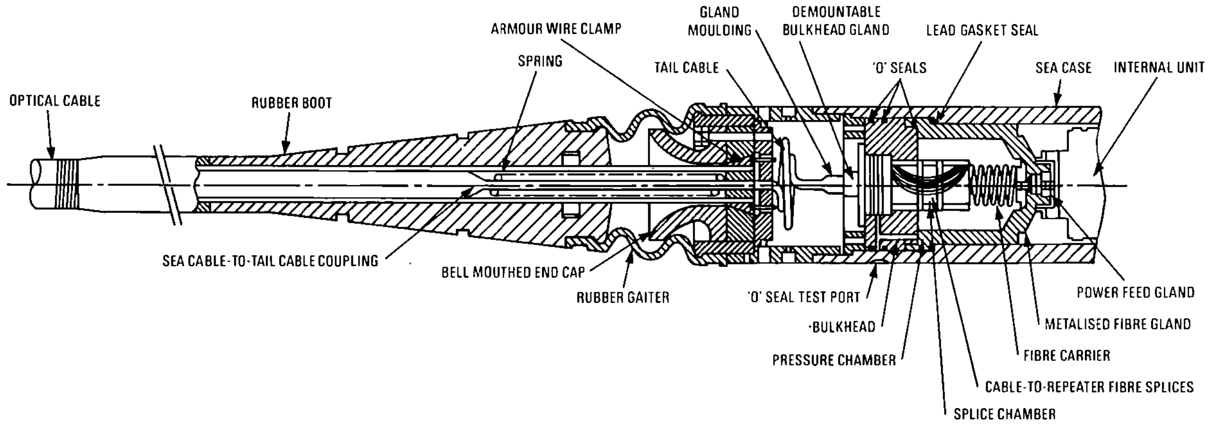

Fig. 2—UK-Belgium No. 5 termination

tar reinforced with glass fibre. An alternative material is beryllium copper alloy, which has intrinsic anti-corrosion characteristics and therefore requires no protection.

A further approach is the use of a stainless-steel cylinder with two aluminium alloy covers for pressure resistance. It is then made watertight and insulated against sea water by a polyethylene coating which provides efficient protection against saline corrosion.

Another function of the repeater housing is to control the internal environment. Hydrogen can have a detrimental effect on the opto-electronic components within the repeater and therefore must be prevented, as far as possible, from entry into the chamber. Often, chemical absorbants for both hydrogen and water moisture are placed in the housing to keep both within acceptable limits for the life of the system. Generally, the internal units are filled with dry air or evacuated, and back filled with oxygen-free dry nitrogen immediatly prior to closure.

The reliability of the electronic components depends upon keeping a low temperature within the repeater. The casing therefore must provide a good thermal dissipation path to the surrounding sea. This is achieved either by direct contact of the internal unit with the inside wall of the casing or by utilising the springs on which the internal units are mounted for shock isolation.

The housing is sealed at each end by removable high-tensile alloy steel bulkheads. By means of neoprene O-seals, which are located in circumferential grooves around the bulkhead, and a lead gasket gas seal which is caused to 'flow' under pressure, an effective seal is obtained in the radial gap between the bulkhead and casing.

Fibre and power-feed penetration of the bulkhead to the splice chamber is via the demountable bulkhead gland in the centre of the bulkhead. The fibres and power-feed conductors enter the bulkhead gland along the tail cable. Glanding to the tail cable is achieved by a polythene injection moulding over a castellated bulkhead gland stem, and onto the tail cable sheath. The design of the moulding ensures that the effect of sea pressure enhances sealing onto the gland stem.

SPLICE CHAMBER

The splice chamber is an area within the bulkhead (see Figs. 3 and 4, which show alternative configurations) where the internal optical-device fibres are spliced to sea-cable fibres. The power-feed conductor is also connected in this chamber.

The chamber is attached to the demountable bulkhead gland and protects the internal units against axial ingress of water or gas along the cable. Accordingly, it has been designed for ease of assembly and disassembly in the depot or on board a cable ship.

During cable-to-repeater assembly, access to the splice chamber is achieved by withdrawing it through the main bulkhead central bore; the coiled excess fibre stored in the chamber enables this to be done.

The integrity of the splice chamber can be checked by pressurising it with helium and checking for leaks around its periphery with a detector. In service, the splice chamber compartment, and frequently the tail cable, are pressure filled with a compound that is compatible with the cable water-blocking material to prevent possible moisture ingress of water or gas in the event of nearby cable damage. Materials used as a water-blocking compound are polybutenes, polyisobutylene or petroleum jelly.

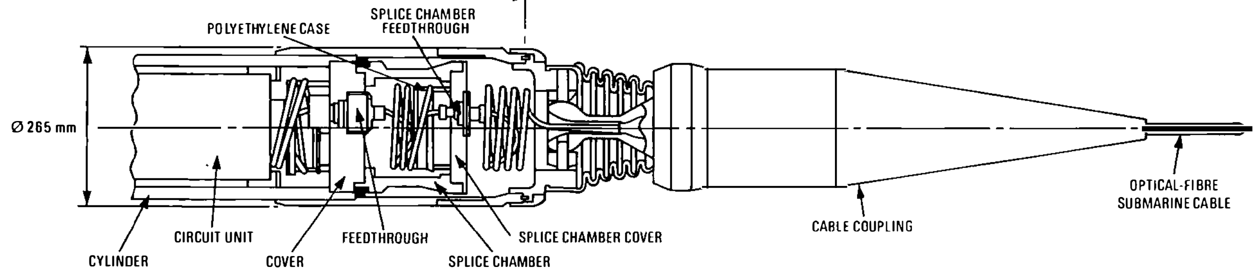

Fig. 3—Repeater glanding system and splice chamber

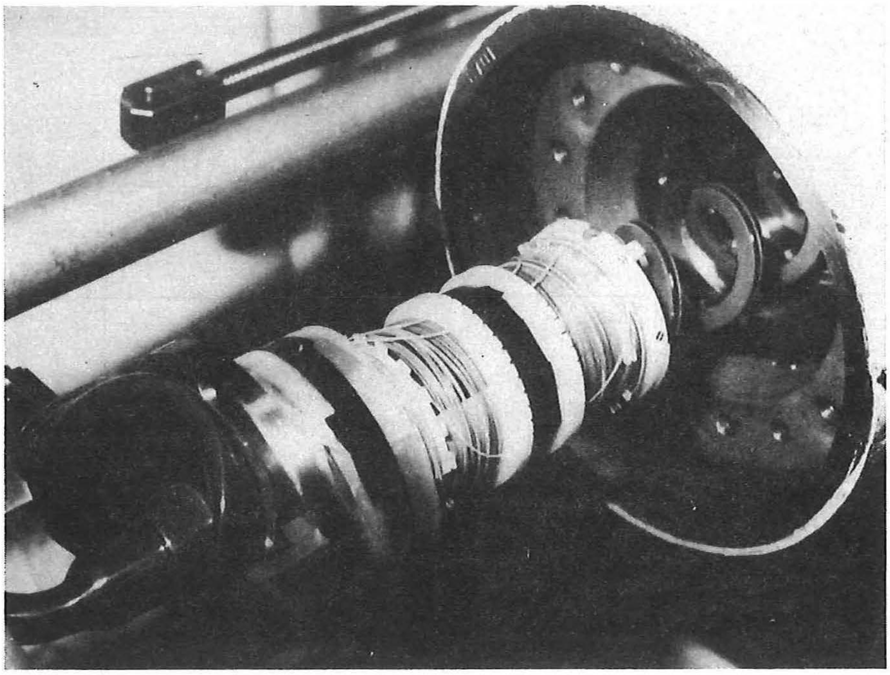

Fig. 4—Section of a UK–Belgium repeater showing, from the left, pigtail connected to the bulkhead, splice chamber with two bobbins containing excess fibre, and fibre carrier

DEMOUNTABLE BULKHEAD GLAND AND TAIL CABLE

Whilst the optical-fibre package is protected against the tensions and bending strains of marine operations by the cable structure, this task must be taken over by the cable-to-repeater interconnection device at this high-risk interface. This imposes additional demands on flexibility and load transfer.

The problem is overcome by coupling the fibre package to the regenerator via a small-diameter flexible tail cable. To provide the flexibility and extensibility for ease of coupling assembly, this tail cable is coiled and hence is known as the *pigtail.*

Fibre and power-feed entry to the internal units is frequently achieved by a two-stage solution. In the initial stage, the fibre package enters the bulkhead gland via the tail cable, which comprises a pressure-resistant metal tube externally sheathed with polyethylene. This high-pressure metal tube, typically made of copper, stainless steel, brass or some other alloy, also acts as the power-feed conductor. Glanding to the tail cable is achieved by a polyethylene injection moulding over a castellated bulkhead gland stem onto the tail cable sheath. The moulding is designed so that sea pressure enhances the sealing. Over the length of the bulkhead gland, the metal tube is replaced by a similar metal tube but with an external machined thread form. The bore of the demountable bulkhead gland through which the tail cable penetrates is also threaded. During gland moulding, polyethylene is forced into both thread forms and provides mechanical locking to prevent extrusion of the tail cable components through the bulkhead under the effect of external sea pressure at depth.

Demountable bulkhead gland and tail-tube assemblies are subjected to extensive factory testing before assembly. Production glands and tail cables are subjected to visual and X-ray examination for moulding defects and inclusions, followed by hydraulic pressure tests at full system pressures. During these pressure tests, the insulation resistance is checked at 40 kV DC. Such endurance tests frequently last a month or more so that water and gas leakage can be monitored.

GLANDS

Second-stage fibre and power-feed entry to the internal unit is at the pressure chamber. Power-feed penetration at the pressure housing is achieved by individual high-voltage power-feed glands of glass and nickel-cobalt ferrous alloy construction. The sealing method to the pressure chamber is provided by a double O-ring system. The first of these, a rubber O-ring, provides the high-pressure hydraulic barrier, and the second, a metal O-ring, the high-pressure gas barrier. Visual inspection is made of the power-feed gland prior to assembly of the system. Helium gas leakage pressure testing at 77 MPa reveals leaks of less than 0·5 cm^3 over a 25 year life, determined by a mass spectrometer detection technique. There is also an electrical test to check for 36 kV voltage breakdown capability as well as checks for leakage currents.

The transmission fibre seal has to be capable of withstanding maximum sea-water pressure, say 77 MPa. The use of epoxy-resin adhesive for sealing optical fibres is to be avoided as most resins degrade their strength in sea water or in the presence of moisture, and so long-term reliability is in doubt. Instead, metallic solders of various alloying mixes are preferred either on the primary-coated fibre or onto bare fibre. For a perfect airtight seal, the primary coating has to be removed, but this procedure often reduces the fibre strength and creates greater vulnerability. One system, however, involves soldering onto a polyamide resin coating, a material which has excellent thermal resistance, chemical stability and adhesion to the glass fibre. The secondary coatings are removed and a copper and gold layer is metallised onto the polyamide coating. This affords excellent tin-lead solderability to the fibre. In this instance, the fibres are laid in grooves around a pin with a close-fitting sleeve, the thermal contraction of which after controlled temperature soldering provides a tighter fit. The pin and sleeve surfaces are also plated for improved adhesion, with the solder orientation improving the seal when under pressure. Corrosion is prevented with a polybutene infill to the gland cap. The quality of the finished product depends upon the quality control of the preparation and manufacture. Air cells in the solder will create pressure collapse, and bent fibre will give increased loss. Great care is thus required

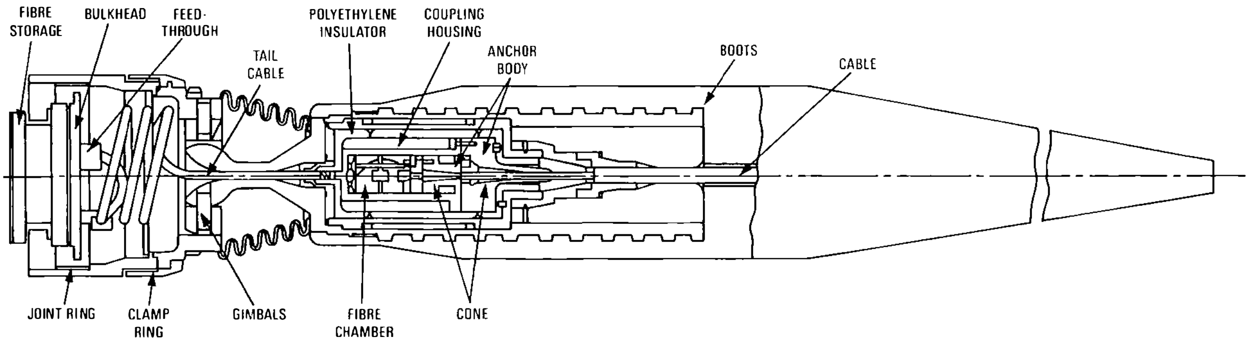

Fig. 5—Structure of cable coupling

in manufacture and handling. The glands are tested with temperature cycles, water-pressure cycles, gas leakage, vibration and shock cycles.

A superior technique is that of metallising the bare glass fibre. In this instance, optical-fibre penetration is achieved by using individual optical-fibre glands, manufactured in the centre of discrete fibre lengths which are subsequently spliced into the system between the optical device and the fibres in the sea cable.

The gland manufacturing process consists of a few metres of fibre being wound equally onto two spools within special cassettes, the central part of the fibre being available for processing. The secondary coating is removed with a hot-air gun, followed by the primary. The pair of cassettes, with the central couple of centimetres of fibres bared, are then transferred via a special jig into a high-vacuum chamber. A combination of metallic layers is then deposited by sputtering onto the fibre to provide a base for soldering. The appropriate thicknesses of chromium, cupronickel and gold give improved hermeticity. The gland stem is then soldered with a bismuth alloy to the metallised fibre. Precision techniques are used with a forming gas to obtain a good sealing meniscus. Tubular supports are then screwed to each end of the gland covering the shoulder of the secondary coating and filled with an epoxy resin. The metallisation and solder, which are then completely encapsulated and protected against corrosion, are at least as robust as the original fibre. The individual glands are located in the pressure chamber bulkhead. Again, the sealing is provided by a rubber O-ring as well as a copper washer.

The glands are subject to visual inspection, and then water and helium-gas leak detection at pressures of 77 MPa. Leak rates of less than 1×10^{-8} cm^3/s can be achieved as well as a loss of less than 0·1 dB at 1·3 μm transmission wavelength.

CABLE-TO-REPEATER COUPLING

The cable-to-repeater coupling is the mechanical arrangement for transferring all of the strength and induced torque of the cable directly to the repeater housing with complete flexibility of movement, but yet transmitting no strain to the optical or power-feed paths. The external part of the termination is configured to eliminate significant bending from the main sea cable, and to provide a smooth profile from the housing diameter down to the cable diameter by means of tapering rubber boots. The coupling is thus capable, within the bounds of the length of the repeater housing, of being passed around a ship's cable engine or 3 m diameter bow sheaves without special treatment. Couplings are available for the full range of armourless or armoured cables. The armour wires are suitably gripped so that the mechanical performance of the cable is transferred faithfully through the coupling to the housing.

The nature of the coupling can vary, as can the degree of articulation offered. Tight conformance with a cable engine drum seems the most desirable, with an angle of 90° between cable axis and housing axis being the maximum achievable. In general, a beryllium copper double gimbal is used to connect the repeater housing to the pigtail sea cable joint or splice box. The gimbal technique (Fig. 5) giving about 57° of bend, has been well established in coaxial technology; the only addition is the optical-fibre joint box.

A more elegant solution is that afforded by the *armadillo* (Fig. 6), comprising a series of metal plates of reducing diameter to give a conical profile from the repeater-housing diameter to that of the joint-box diameter. In both armourless and armoured versions, the steel plates are loosely held together with bolts affording total flexibility of more than 70°. For safety reasons, the armadillo is covered with a gaiter, but does not require a profiled boot.

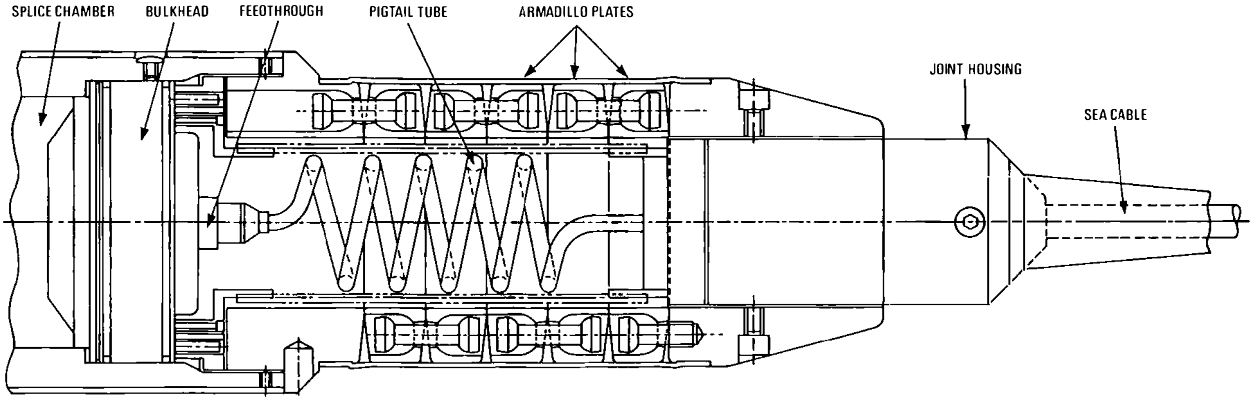

Fig. 6—Lightweight tensile armadillo bend limiter

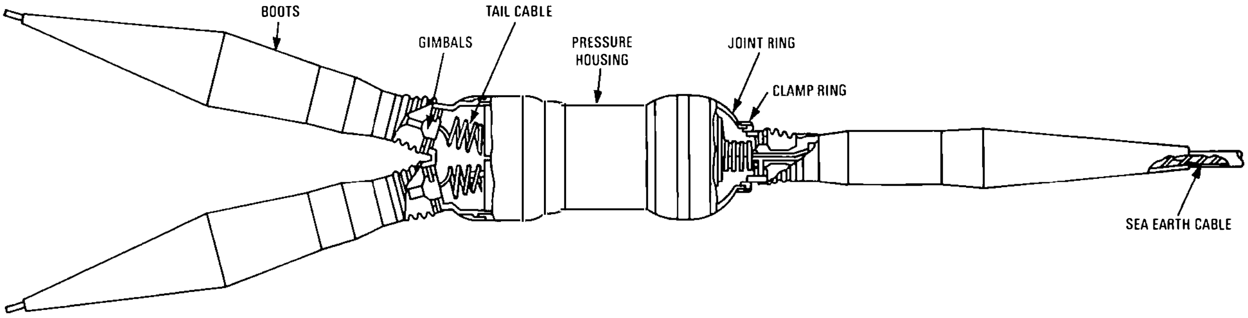

Fig. 7—Schematic of cable-to-branching-unit coupling

The splice box or junction box attached to the coupling, in all cases, is derived from the sea-cable repair joint. Sometimes, there are minor variations, but the same principles are required. An air-tight and water-tight chamber is required to store fibre and perform splices from the sea cable fibre to the fibre in the pigtail tube. An easy mechanical assembly is required between the cable termination and repeater.

Besides providing a water barrier in the power-feed and transmission-fibre pigtail tube, an additional water barrier can be provided in the termination box. For factory manufacture or marine shipboard repair, it is desirable for the termination box to be the same or very similar to the sea-cable repair joint box.

In one solution, the mechanical continuity with the repeater housing is achieved by a glass-reinforced epoxy-resin case to match the overmoulded junction box. A beryllium-copper gimbal is used, and torque transmission is achieved by reliefs in the polyethylene moulding of the armourless termination box. For the armoured cable coupling, the same design is used, but the armour wires are individually crimped with small ferrules locked in the epoxy-resin case by the presence of the termination box. The merit of this system is that the armoured cable is electrically insulated from the regenerator housing, the linking metallic gimbal being only physically connected to the glass-reinforced epoxy-resin components. The pigtail connects to a device within the epoxy glass housing.

In all other instances, there is full metallic continuity from the armouring through the armadillo or gimbal to the repeater casing. In these cases, the coupling termination is essentially identical to the joint arrangements. The only variation on the all-metallic solutions appears to be the technique of holding the armour wires. These vary from individual crimping of the wires into suitable supports to mechanically-located conical clamps to hydraulic sleeve swagings onto a hardened support tube.

Finally, the technology of optical-fibre submarine cable systems offers a diversity in the form of branching units (Fig. 7). Here again there is an extension of the recent technological developments to accommodate two terminations to one end of a repeater housing. The concept is identical to the normal cable-to-repeater termination but, of necessity, is assembled on board ship. Power can be fed to each or all of the cables connected to the branching unit.

CONCLUSION

The development of the optical terminations is a readily forseeable enhancement from coaxial technology. The only novel advancement is the elegant solution of the armadillo concept. By means of a pigtail on each end of a repeater housing and a cable joint capability, the special cable terminations of the coaxial era are now no longer required. The mechanical coupling is readily assembled and removed.

Biography

Tony Gould graduated from Leeds University in 1972 with a B.Sc. in Mechanical Engineering. That year, he joined British Telecom working on the theoretical aspects of coaxial and, later, optical-fibre submarine cable design. In 1984, he assumed responsibility for all aspects of optical-fibre submarine cable, jointing, terminations and associated technology.

Submarine Cable Design Requirements and Testing

C. A. GOULD, B.SC., C.ENG.†

UDC 621.315.28 : 621.391.63

The general design of an optical-fibre submarine cable is complex and requires the optimisation of a number of mechanical, electrical and optical parameters to give the cable the required performance characteristics at a realistic cost. Some of the factors that have to be considered in cable design are protection against the working hydrostatic pressure, water ingress, hydrogen susceptibility, tensile strength, and resistance to wear and fatigue. In addition, the operating performance of the cable has to be predicted under various conditions. Thus, a comprehensive series of tests is undertaken to ensure that the cable will be satisfactory over the life of the system.

INTRODUCTION

In considering the construction of an optical-fibre submarine cable, a careful balance must be struck between two apparently extreme requirements; namely, operation in the harsh marine environment, and the provision of a relatively benign environment for the optical fibre transmission path. Thus, there is considerable scope for interrelated design trade-offs involving the selection of materials and make up of the cable. Such flexibility is, however, limited when the manufacturing constraints and the practicability of installation are borne in mind. Over its lifetime, the cable has to withstand storage, laying, possibly burial and detrenching, holding to the bows of a ship for a repair, as well as being capable of being jointed in a simple and speedy manner. These needs are of paramount importance for a cable system with a projected life of 25 years. It is also important to recognise that the cost of a cable represents a significant proportion of the total system cost.

For any submarine cable system, cables of varying structure are required to cater for deep-sea pressure-resistant applications, shallow-water fishing and anchor resistant locations, heavily-armoured beach cable, and finally an earth safety-screened cable routed via ducts to the terminal building to connect with the terrestrial network. It is clearly preferable that a single compatible base design is used for these various applications, with additional structural features applied to enhance the specific physical capabilities to meet the appropriate need (see Fig. 1). It must be remembered that the following aspects are interrelated and must not be considered in isolation.

FIBRE AND PACKAGING

The transmission medium for optical submarine systems is single-mode silica fibre, typically 125 μm in diameter with an 8 μm core, with lengths after proof testing ranging upwards from about 2 km. Therefore, any submarine system must comprise many lengths of individual fibre, each and every one accurately aligned and spliced to its neighbour. For immediate protection of the fibre after drawing, it is often coated with a soft primary material to act as a mechanical buffer layer. Some manufacturers then take the primary-coated fibre and subsequently coat it with a harder more-durable mechanically-stronger plastic layer, depending upon the water-blocking and strain-relief techniques used in the cable design. The fibre is then in a durable form suitable for handling through cable manufacturing machinery. It is typically stored on reels containing a few kilometres in length. The optical loss characteristics of each reel are then measured and those that are within limits can then be loss matched and concatenated prior to being colour marked with a dye for later identification. The silica fibre is arc or flame fused and the coatings restored to the original manufactured diameters.

Fibre life until failure is related to the duration of its axial tensile strain. This effectively creates fibre ageing, imposing increasing limitations on the marine operating margins during a cable's life. As the secondary coating is often applied as a tight cladding and as it is a relatively stiff material, there is some scope for adjusting the thermal contraction coefficient of the coating material to create axial compressive strain in the silica fibre. The merit of this novel feature will be explained later, but the advantage is that the secondary-coated fibre can be proof strained to one particular tensile strain value; there being a lesser value induced on the silica transmission fibre within it. This has a useful advantage in that the tested yield of the fibre after manufacture is increased. The higher the value of proof strain, then generally the lower the yield due to a higher incidence of fibre breakage.

The purpose of setting and testing to a minimum proof

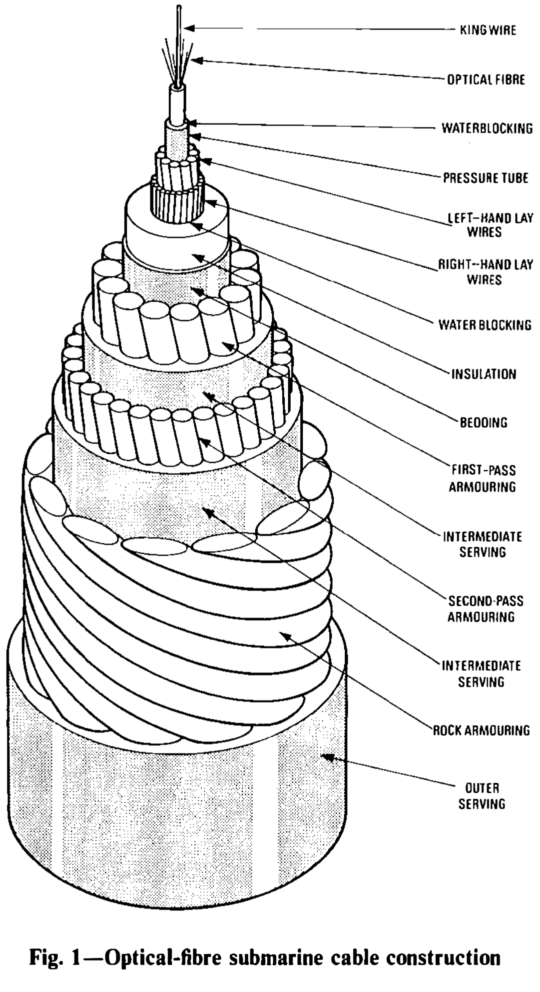

Fig. 1—Optical-fibre submarine cable construction

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† Technology Applications Department, British Telecom Development and Procurement

strain figure is an endeavour to eliminate that quantity of fibre with an inherent flaw greater than a certain size. The actual practice of proof straining fibre in itself reduces the eventual life of it marginally. However, fibres that pass successfully should be assured of surviving a certain strain value after a certain period of time. For current fibres with their anticipated environment within a cable, the manufacturer's proof strain is set at about twice that operationally needed at the end of its 25-year life to satisfy the most demanding operation of deep-water recovery. This two-to-one ratio has been empirically determined from laboratory tests.

The proof strain value for the fibre within a submarine cable structure is thus determined by the maximum anticipated operational strain on the submerged cable during its projected life. The strain upon the cable is determined primarily by the maximum depth of water to which it will be laid and the actual structure itself. Great care must be taken in the design and operation of an optical-fibre cable to ensure that throughout its life the allowable fibre strain is not exceeded, even during periods of recovery from deep water. There is a need to guard against the possibility of fibre failure within an otherwise structurally intact cable. Clearly, a strong light structure will elongate considerably less than a weak heavy one.

The relationship of the tensile breaking strength of the cable to its submerged weight is called the *wet cable modulus* and is expressed in units of nautical miles. This gives the maximum length of cable that may be ideally suspended vertically before breakage occurs, and this generally exceeds 10 nautical miles for deep-water cable designs. As the cost of all the fibres within the optical package represents a very significant proportion of the total cost of the finished cable, a balance must be found between increasing the proof strain value of the fibre, with a lower yield and hence an increased cost; and increasing the strength and less proportionately the weight of the cable, and hence an increased material cost. This relationship must be optimised for each generation of cable types. As time passes, higher-strength fibres will become increasingly available for the same or lower cost, so a trend towards smaller deep-water cable structures may become evident.

There are two approaches that allow the proof strain of the fibre to be reduced, one is to increase the overall strength of the cable and the other is to design for strain relief, so that when the cable is tensioned, the optical fibres experience a strain smaller than that in the cable structure. This latter objective is achieved by manufacturing fibre with secondary coating precompression, or by allowing freedom of fibre movement in loose tubes or grooved containments, with or without a thixotropic medium. A thixotropic gel allows dynamic fibre movement by becoming liquid, whilst providing viscous support when static.

The fibres themselves, individually coloured for identification, are then laid individually or collectively within the cable structure with a helical or parallel lay. While the choice of fibre parameters allows some scope for minimising the additional loss due to microbending or proof-strain testing effects, it is nevertheless important that such microbending itself is minimised. This is often achieved by incorporating a soft cushion layer into the fibre coating, but other techniques include embedding primary silicone-coated fibres into an elastomer cushion layer. If they are placed individually, they are frequently put into grooves or loose tubes around a former and held in place with some form of thixotropic gel. If placed collectively, they are frequently helically whipped with a fine binding cord to hold the package of fibres together. In this instance, they are also laid up around an inextensible king wire, not only for axial strength for the manufacturing process, but also to provide some rigidity and constraint against lateral bending or buckling damage during processing.

For a typical cable construction, the transmission fibres are offset to the cable neutral axis by a distance of 1–2 mm. For a bending radius of 1 m on the cable structure, this will create a certain bending strain in the outside surface of the fibre. Clearly this gives a minimum strain for which allowance must be made. In addition, normal cable manufacturing will leave a residual strain in the fibre construction. This must be added to the bending strain. If the end-of-life strain requirement on the fibre is typically 0·6%, then subtracting the composite fibre surface strain indicates the allowable laying and recovery strain. This figure also indicates what benefit may be achieved by the concept of inbuilt strain relief. The strain relief can be as much as 50% of the operating margin. A desirable feature to reduce fibre bending losses is to locate the fibres as close as possible to the neutral axis of the cable. To achieve minimum strength deterioration due to static fatigue, the residual strain left in the optical fibre after cabling should be as small as possible. Typically, values of residual strain of less than 0·05% have been achieved[1].

A parallel lay of fibres has the advantage of ease of manufacture and of separation for repair. The advantage of a helical lay of fibres is that when the package is drummed, the bending stresses are equalised, but at the expense of a more complicated manufacturing process. The package may or may not be oversheathed and could be about 2–3 mm in diameter.

WATER AND HYDROGEN BLOCKING

A further consideration is that of water blocking the cable structure to limit the penetration of sea-water ingress in cases of accidental severance, and thereby to minimise the length of cable that may be adversely affected. Optical fibres are highly sensitive to sea-water, and must be protected against this, or made as invulnerable as possible. When the cable system is repaired, prudence would indicate that all lengths of cable with traces of water should be cut out of the system and replaced. Consequently, for any cable design, the water propagation rate axially along the structure is a prime concern. For a constant driving pressure and constant intersticial area, the water propagation velocity is constant. This can be limited by filling all orifices to produce a fully water-blocked cable. However, if the blocking material or process is not perfect, there is the possibility that the overall water propagation rate is in fact faster than in the unblocked cable. The manufacturing problem is to find a material that can be injected into all interstices with no detrimental effect on the properties of the cable or of the fibre, but will be effective and ensure that the overall propagation rate is slow enough to prevent the water ingressing great distances along the cable before the arrival of a repair ship.

Another consideration for a fibre-optic transmission cable is that of the hydrogen generation of all the cable components. This is because of the particular sensitivity of the fibre at the current operating wavelengths to increased loss resulting from the presence of hydrogen. Cable materials must be considered for their individual and interactive collective contribution to hydrogen generation. This may either be in a sea-water medium external to the cable structure or in the water-to-fibre interface internal to the cable structure. A cable designer would examine many such materials in isolation and together in cable designs before finally deciding the optimum materials for the structure. A recent development that makes the transmission fibres much less susceptible to the effects of hydrogen is of metallised fibre coatings. Additionally, there is research directed towards triaxial glass structures which would achieve the same end.

PRESSURE TUBE AND POWER FEED

The main features of fibre-package protection are to maintain transmission, minimise microbending, and to give no radial reduction of the cable structure around the fibres, either directly or by means of hydrostatic pressure through a thixotropic medium. The essence of a good cable design is to utilise the material forming the hydrostatic pressure barrier in an efficient manner, but within the limits of total stability. This effectively hollow structure must withstand not only the maximum operating sea pressure, but superimposed with all the expected preceding handling abuses of the cable. The pressure-resisting tube often serves also as a water barrier and as a substantial part of the power-feeding conductor. Thus, there is often a consideration of a minimum cross-sectional area required for the purposes of DC power feeding which is rather greater than the material solely required as a pressure housing. For these reasons it is not optimised at the absolute limit for pressure. Such a pressure tube is frequently made from a soft formable conducting metal such as aluminium or copper.

The pressure resistance of a cable structure can be achieved in two separate ways or, more generally, by a combination of ways. The first is a metal-tube design where there is a sufficiency of metal wall thickness to prevent direct hydrostatic crushing, though this is critically dependent upon the Young's modulus for the material chosen. If overpressure does occur, then a predictable stable plastic crushing performance is required. Alternatively, or sometimes in addition, a steel-wire structure can be used whereby the contact between the helically laid steel wires gives an arch bridging effect. This is especially so even if only lightly supported in the appropriate geometric position. Clearly though, the number of wires is optimised at about a dozen; fewer wires become large and unwieldy for the area they are protecting, and too many wires become readily unstable, both in the final structure and during manufacture.

For the purposes of powering regenerators on any long-haul system, a power-feed conductor is required. The DC resistance offered by different metals must be considered either in isolation or as a combination with the aim of providing an overall resistance of about 1 Ω/km. In addition, long-term contact corrosion must be considered as well as the cost and ease of manufacture when different metals are used. The low DC resistance advantages of copper are partially offset by its higher material cost and weight penalty. The DC resistance of the steel which exists in most cable designs on account of its strength is insufficient by itself to meet this criteria and therefore has to be used in conjunction with some other lower DC resistance material. Aluminium is rather less effective than copper, but has the advantage of lightness. However, the overall bulk of material must be minimised in order to reduce cable weight and hence extensibility.

STRENGTH

Nearly all submarine cables have a single or multiple steel-wire strength member that is common to all cable variants in the system. This is principally for ease of jointing by giving commonality to the strength component and the splicing system so that a cable break may be repaired and the associated section restored. The requirement of the strength member is that it must withstand not only the vertical cable load when being held at the bows of the ship, but also the dynamic forces that are superimposed during laying, but more especially during recovery. In the case of partially-silted or buried cable, there are also the additional sea-bottom detrenching forces. Thus, during a cable's life of manufacture, transportation, storage, handling, deployment and repair, there must be no impairment of any of its design properties.

If damage is likely to be caused by physical entanglement, resulting in tensile strains, it is desirable that the fibres should not break or be significantly weakened prior to imminent failure of the complete cable structure. Clearly, transmission failure within an otherwise intact physical structure must be prevented. Therefore, the cable and its variants must be sufficiently robust to withstand all marine eventualities and yet have a failure strain not that different from the fibre itself.

The maximum working fibre strain must be evaluated to achieve a 25-year life by using the typical failure strain of about 1% for high-tensile steel wire used in armourless cables and knowing the weight of the cable, depth, and expected loads. This enables the required strength to be determined, expressed as a wet cable modulus in nautical miles. Some designs have an additional benefit by employing strain relief whereby the fibre strain and cable strain are not directly equal, but where the fibre strain lags that of the cable strain by an inbuilt desired amount. High-strength cables are to be preferred from the viewpoint of placing lower strain on the fibre during deployment, but this must be balanced against the increasing cost of materials and manufacture, and the proof strain of the fibre as earlier mentioned.

If the strength of the cable is increased so that the strain at the maximum load is compatible with the proof strain of the available fibre, allowing for strain relief, this leads to structures of one or two strand layers laid around the cable core. The 2-layer designs are generally torsionally balanced, providing greater axial stiffness; a single helical-layer of steel wire will cause the cable to rotate in a gentle unwinding fashion when loaded. Not only is there natural extensibility of the steel wire material, but also there is the additional extension due to the geometrical change caused by unwinding. A torsionally-balanced cable also gives further advantages during deployment insofar as it does not cause loops or kinks to be thrown into the cable at the sea bed. With the pitching movement of the ship, such torque-generated loops can tighten and cause transmission failure within an otherwise structurally intact cable. This is wholly unlike coaxial cable where the transmission path fails only upon severance of the physical structure.

For the given size of the cable, the manufacturer selects wire sizes and numbers to give the required performance for the grade of steel material chosen. For a torsionally-balanced cable, each layer of wires at its radius and helix angle will create potential rotation; these will be matched to be equal and opposite. Clearly, the outer layer of wires will be smaller and more numerous than the inner layer. Manufacturers can lay-up such a cable in a single manufacturing operation.

INSULATION

The next manufacturing stage is to oversheath the cable. For a constant-current power feed, a long-haul regenerated system will need a terminal voltage in the order of kilovolts. Therefore, the outside of the smooth finished metallic structure requires a minimum of 3–4 mm of insulation from the point of view of high-voltage protection. Not only must the operating voltage be allowed for, but, in addition, a surge-voltage component. Therefore, to guarantee this insulation, an additional 2–3 mm of insulation must be allowed to take into account abrasion and chafing, particularly on rough sea-bottom areas. Currently, the optimum diameter of the finished cable product is about 25 mm (1 inch) in order to provide safety and ease of handling on board a cable ship. Historically, the marine laying equipment, a linear cable engine, was designed to accommodate the then smallest coaxial cable of about 25 mm diameter. Ideally, the insulation material must be cheap, durable, water resistant and have an excellent high-voltage breakdown capability. Most often, low-density polyethylene is used as a single extrusion. Sometimes a two-pass extrusion is used with high-density polyethylene on the outside to provide additional protection against marine borers or fish attack. Additionally, for land-based storage, the high-density polyethylene would have carbon black infill to give protection against ultraviolet light degradation.

CABLE JOINTS

An ideal cable joint would have a low-resistance through path for the power-feed conductor, a strength of say 90% of that of the parent cable and a minimum increase in overall cable diameter. The fibres would have the smallest splice loss which the current technology of fibre splicing permits, commensurate with a sufficiently large bending radius of the fibres so that the residual strain in the fibres will not lead to failure within the design life. Since it may not be possible to ensure that all the fibre splices are completed successfully at the first attempt, it becomes necessary to stow a certain amount of spare fibre. In order to do this without violating the minimum safe bending radius, the diameter of the joint housing has to be locally increased by a factor of three or four over that of the cable diameter on either side.

OTHER CABLE VARIANTS

The lightweight, or armourless, cable is that used traditionally in deep-water areas. Of necessity, the lightweight cable is armoured with one or a number of layers of heavy steel armouring wires appropriate to its destined location to prevent trawler damage, say, on continental shelf areas. Steel-wire armouring layers are an expensive means of protection, so cable burial is now adopted wherever possible. This implies that cables require adequate strength to permit a detrenching capability.

Consider now system cable compatibility. It is highly desirable for shallow-water armoured cables to be simply overarmoured versions of the same deep-water design. If the armoured sea joint is simply an extension of the deep-water cable sea joint, again benefits are realised. A similar argument extends to safety-screened land duct cables, where a metallic earthing tape wholly covers the cable, but within another polyethylene extruded coating.

All cable designs should desirably be an interrelated family of cables with the same central package; that is, the same deep-water structure throughout. On top of the basic deep-water structure, either a single-armour or a double-armour of steel-wire protection is chosen, depending upon the expected damage from trawlers or anchors.

This family of cables, however, requires interlinking from a mechanical point of view. Typically, the steel wire used in a deep-water cable has 1% extensibility at failure. Grade 65 armour wire used in single-armour cable designs fails at about 2% strain. Grade 34 wire used in some double-armour cable designs fails at about 4% strain. Thus, there is a need to calculate the relationship between the various cable designs, from the point of view of the stress in the steel-wire material. Clearly, the double-armour cable will have a greater cross-sectional area of steel available than for, say, a single-armour cable. This large area of lower-grade steel, albeit working at a lower stress, still provides considerably enhanced strength over a single-armour cable. Likewise, a single-armour cable is vastly superior to an armourless cable. When laying the series of cable types, an allowance must be made for the weight of the double-armour cable to be supported by the single-armour cable, and for the armourless cable to support the single-armoured cable. In particular, the concept of wet modulus is reintroduced where the inter-modulus through the family of armoured cables is normally about three nautical miles.

A further problem associated with design of a family of cables is the load-transfer problem. Imagine a single-armoured cable that is strained beyond 1% strain. At this point, the central strand will fail at its ultimate tensile strength, thereby throwing all the load that it carried upon the single-armour wires surrounding it. It would be undesirable for the single-armour layer to suddenly absorb this increased load without failing. There would otherwise exist a physically-failed armourless cable residing within an intact armour structure. The same argument holds true for double-armour cable. The steel grades and their sectional areas are therefore chosen carefully and the proportional load sharing determined at all values of strain.

Finally, a complete family of cable designs will be tested for tension and torsion characteristics, pressure and impact resistance, flexural and fatigue performance, and water and hydrogen permeation. Fibre transmission tests would be done at all stages where possible, but finally a system test would involve a sea trial.

An alternative form of cable protection is burial, either with a plough or a submersible. In suitable sea-bottom substrata of sand, mud and gravel, cable can be typically buried up to a 1 m depth. A suitably engineered plough would accommodate armourless, single- and double-armoured cable and a regenerator housing whilst burying, probably without a change of ship speed.

Burial makes it incumbent upon the cable designer to determine axial and transverse detrenching forces for these substrata. The bight recovery and peeling recovery forces can then be determined to ensure a repair facility for the cable in case of anchor damage. It is interesting to note that the geometry of anchor damage can create quite high strains in the cable at quite some distance from the hooking point, so that the fibre life of the disturbed cable may be compromised for quite some distance on either side of the disturbance, insofar as the allowable working strain may have been exceeded. Prudence requires that cable possibly affected in this way should be cut out during a repair operation. Remotely-controlled submersibles are available; these are based on a water-jetting principle for both extraction and re-entrenchment[2].

NOVEL DESIGNS

A clever innovation reported recently[3] is that of using the power-feed pressure tube as a tensile strength member. KDD have now adopted a three-part steel pressure tubing comprising circularly shaped steel tapes which are terminated within the joint housing, thereby contributing to the cable's strength.

The Danish PTT[4] report a cable structure whereby the optical fibres are contained, with excess length, within oil-filled tubes. The joint box enclosure is also oil filled. The optical-fibre package is contained within a lead tube to prevent hydrogen diffusion.

CONCLUSION

It is seen that an optical-fibre submarine cable designer must have regard to both maintaining the fibre transmission properties and the many interdependencies this implies, both with the cable design itself and between its various components.

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Biography

Tony Gould graduated from Leeds University in 1972 with a B.Sc. in Mechanical Engineering. That year he joined British Telecom working on the theoretical aspects of coaxial, and later optical-fibre, submarine cable design. In 1984, he assumed responsibility for all aspects of optical-fibre submarine cable, jointing, terminations and associated technology.

The Design of Production Terminal Equipment for Digital Optical-Fibre Submarine Cable Systems

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This article discusses the design requirements of 280 Mbit/s terminal equipment for a digital submarine cable system. The implementation of the design on the first international system manufactured in the UK (UK–Belgium No. 5) is detailed and compared with the alternative design features of the first long-haul system, TAT-8.

INTRODUCTION

Although the design of submarine system terminal equipment is similar in principle to the line terminal and multiplex equipment of inland systems, there are essential differences. For short-haul systems, an unduplicated equipment is provided, such as that used for the UK–Belgium No. 5 system. On long-haul systems, where there are greater network constraints, a duplicated terminal is employed.

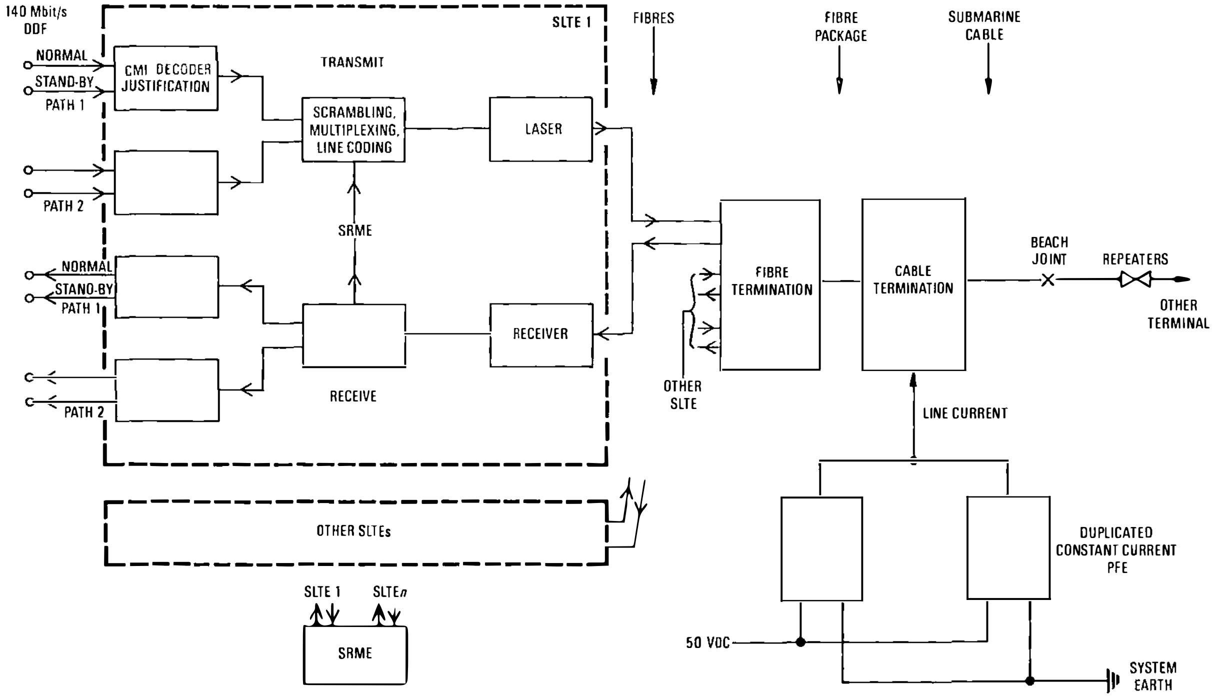
This article considers the design features of terminal equipment for a short-haul system (UK–Belgium No. 5) and briefly compares this with a long-haul design (TAT-8), the UK spur of which is being provided by UK industry.

TERMINAL EQUIPMENT DESIGN

The general features of submarine system terminal equipment are similar to those of its inland system counterpart and include justification, multiplexing, scrambling and line encoding. The main differences are the means of communicating supervisory information to and from the submersible repeaters and the relatively high voltage and currents required for power feeding. A block diagram of typical terminal equipment is shown in Fig. 1.

Terminal Transmission Equipment

The current 140 Mbit/s line interface standard to CCITT*



SLTE: submarine line terminal equipment
SRME: submersible repeater monitoring equipment

PFE: power-feeding equipment

Fig. 1—Submarine system terminal equipment

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† Satellite and Lines Executive, British Telecom International

* CCITT—International Telegraph and Telephone Consultative Committee

Recommendation G.703 has been universally adopted as the basic building block for first-generation submarine systems. The 140 Mbit/s paths can be made up to CCITT European or mixed North American hierarchies[1] with no effect on their transmission capability through digital submarine systems, which are bit-sequence independent. Typically, two of these paths are multiplexed to form a nominal 280 Mbit/s common path. This capacity per fibre pair was adequate for present traffic needs and represented an upper limit to the readily available integrated circuits suitable for terminal station use. Line coding, which may incorporate additional signalling capacity for repeater supervisory purposes, will increase the bit rate above 280 Mbit/s and varies between system designs.

Power-Feeding Equipment

The long spans of submarine systems can only be powered from the two terminals, and the total power required is proportional to the number of repeaters in the system. This generally results in high voltages and currents which necessitate specific safety features and operating procedures to ensure electrical and optical safety for both personnel and the system. In UK designs, the power-feeding equipment (PFE) differs for long-, medium- and short-haul systems. The main differences are the degree of equipment duplication for system security and the need to permanently double-end feed long-haul systems.

Submersible Repeater Monitoring Equipment

On submarine systems, the metallic path for DC power feeding is unsuitable for AC signalling for repeater supervision. Various methods of signalling over the fibres have been demonstrated including clock modulation, as used on UK–Belgium No. 5, and parity-bit violation, as used on TAT-8.

Supervisory control enables the performance of the repeaters to be monitored in-service and more comprehensive tests, including optical-path switching, to be carried out with the system out-of-service.

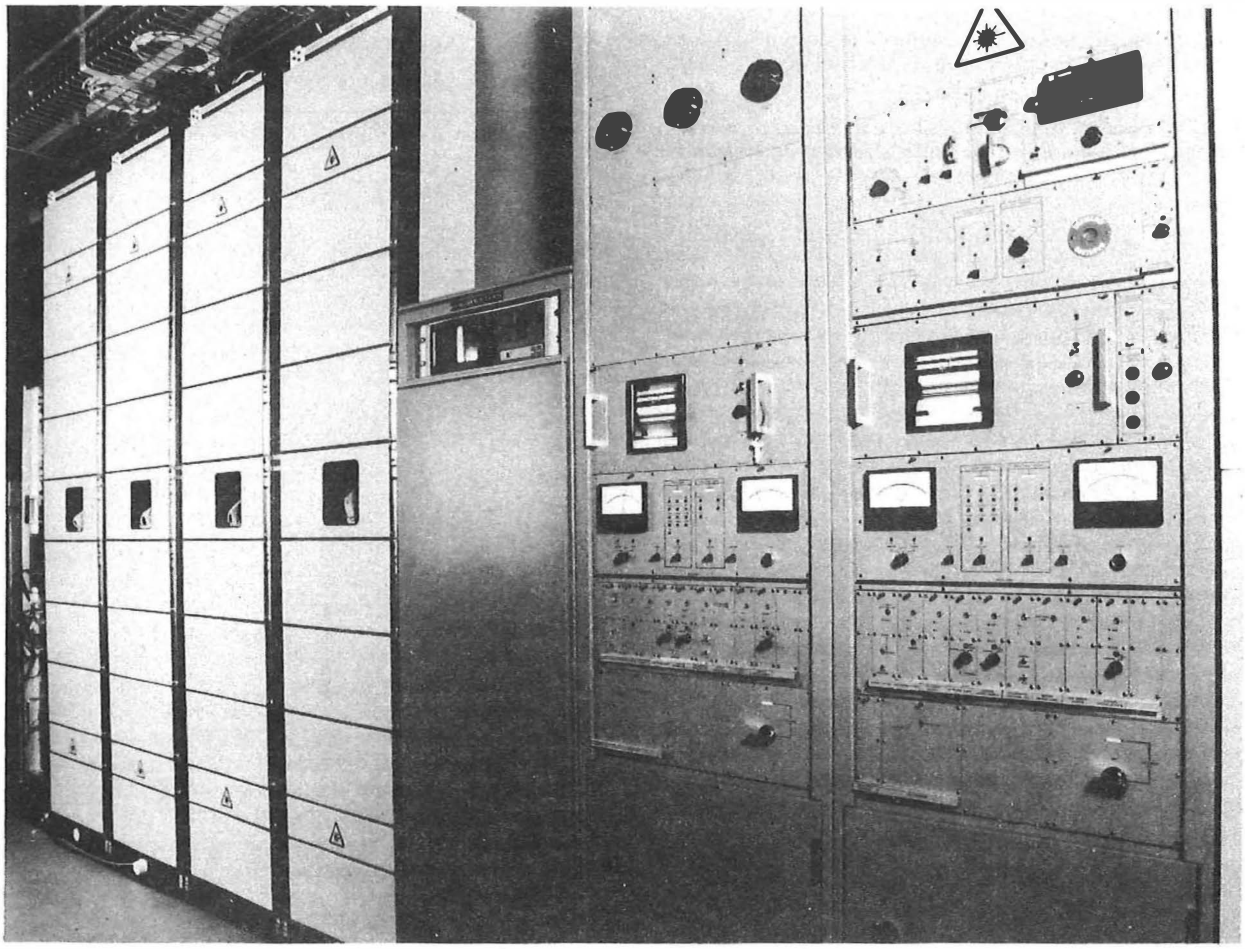
THE UK–BELGIUM No. 5 SYSTEM TERMINAL EQUIPMENT

The UK–Belgium No. 5 system is the initial application of the first generation of optical-fibre systems developed in the UK for submarine cable systems. A contract was placed in 1983 with STC plc for its NL1 system to be installed between Broadstairs, in the UK, and Ostend, Belgium[2].

The equipment was designed by STC, but with the involvement of British Telecom throughout the initial conceptual stages. The design from the outset was intended to produce a commercial product which was fully specified, engineered and qualified for production.

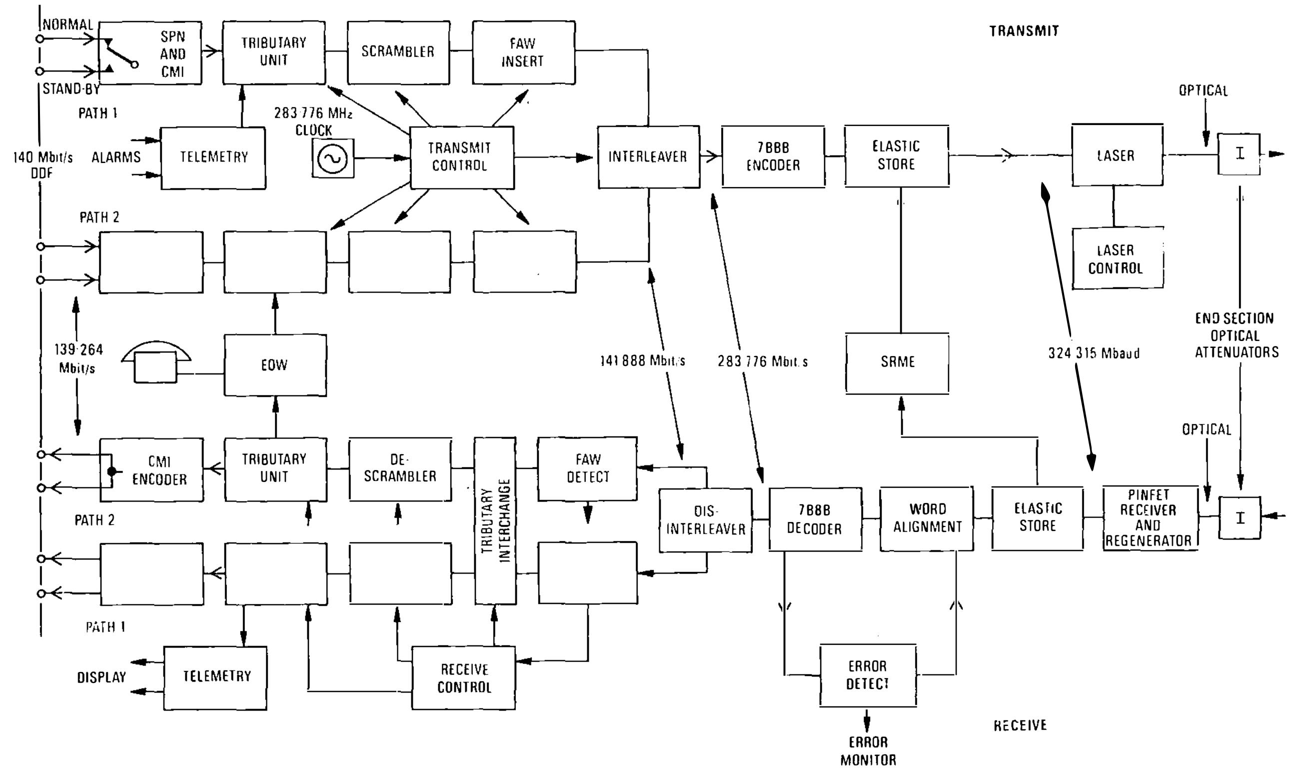
Terminal Transmission Equipment

The terminal transmission equipment (TTE), together with an outline block diagram, is shown in Figs. 2 and 3, respec-



Left to right: 4 SLTE racks, SRME, 2 PFE racks

Fig. 2—UK–Belgium No. 5 terminal equipment at Broadstairs



Note: Several SLTE form one terminal transmission equipment (TTE)

Fig. 3—NL1 system: submarine line terminal equipment (SLTE)

tively. The TTE comprises several submarine line terminal equipments (SLTE), one for each fibre pair.

Construction

Each SLTE is contained within one TEP-1E rack, the construction practice currently in use by BT for transmission equipment[3]. The rack face layout for one SLTE is given in Fig. 4.

The high digital rates used require the use of high-speed emitter-coupled logic integrated circuits with their resultant high power dissipation. Heat is dissipated by convection on TEP-1E equipment for improved reliability over forced-air cooling. At the bit rates used, the propagation time in the interconnection cabling and the tracks of the printed-wiring boards (PWBs) can easily exceed the basic bit period and this could be a problem in the tributary paths, where precise synchronisation between similar electrical stages on different shelves is important. These constraints have a large influence on the equipment layout, which must also be ergonomically sound and provide easy access for operational monitoring, testing and fault finding.

Redundancy

During the development of the terminal equipment, it was decided that the best method of locating faulty cards would be to provide a fully-equipped spare rack. This rack is identical to the operational racks.

Transmit Path

The transmit path comprises two tributary channels each taking a nominal 140 Mbit/s signal as serial data. These are provided with a frame structure and justified. The two signals are scrambled prior to interleaving and the common signal at 283 Mbit/s passes through a line encoder and elastic store prior to the laser modulator. The optical output of the laser on a ruggedised single-mode fibre is then fed to the PFE for connection to the submarine cable.

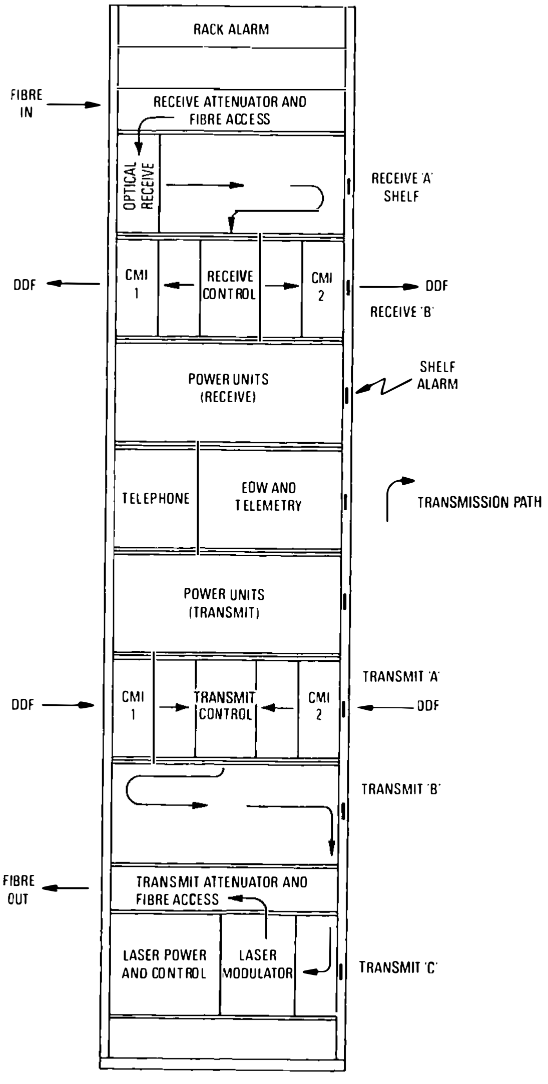
Coded Mark Inversion Decoder

The input to each SLTE is a 139 264 kbit/s ± 15 ppm coded mark inversion (CMI) interface signal, connected via the digital distribution frame (DDF). Normal and stand-by inputs are provided to allow the operating administration to interconnect the submarine system with a service protection network, if required. These facilities are identical with inland system practice.

The signal is decoded into binary, and a data-detect circuit checks whether or not a valid signal is present. If not, the CMI decoder generates an all-ONES alarm indication signal (AIS). This signal is used in the digital network to suppress alarms on succeeding systems.

Transmit Tributary

The bit rate of the two tributary paths is increased to a common rate of 141·888 Mbit/s prior to interleaving; the data is read into a buffer by using the derived 139·264 MHz clock, and the justified data is read out by using a 141·888 MHz clock. At this stage, the 141·888 MHz clock is provided with gaps into which the frame alignment words (FAWs), justification control and service bits are inserted at a later stage.



DDF: digital distribution frame

Fig. 4—NL1 system: SLTE rack face layout showing direction of transmission

The framing structure used in this process is given in Fig. 5. Of interest is the service digit time-slot in set 7. This can be used for various options such as engineering speaker circuits and telemetry between terminals.

The frame timing logic is driven from a 283·776 MHz reference clock. This produces all the control timing including frame and set markers, justification control and service digits.

Scrambler

The signal is then randomised to produce a uniform spectral content by using an 11-stage set-reset scrambler. The pseudo-random sequence is reset by the FAW at the start of each frame. After the scrambler, the two frame alignment words identifying each of the two tributaries, are inserted in their assigned gaps in the output data.

7B8B Codec

The two tributary paths are combined by the interleaver, which simply selects bits alternately from each path under the control of the 141·888 MHz clock and provides a common output clocked at exactly twice this rate; that is, 283·776 MHz.

The combined data is formed into 7 bit parallel words and fed into the line encoder. The 7B8B encoder was designed by BTRL and adapted for this system by STC. The 7 bit words are used both to address the 7B8B read-only memory (ROM) and a separate disparity detect ROM. The latter circuit monitors the accumulated digital sum and provides an eighth address bit for the 7B8B encoder ROM so that an output word of the appropriate disparity is selected to minimise the running digital sum.

The encoder action raises the line rate by 8/7 to 324·315 Mbaud. This line rate is phase locked to the 283·776 MHz reference clock and and becomes the line rate for the submersible plant.

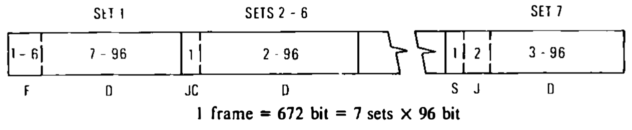
Elastic Store and Pattern Generator

A serial output buffer and a complementary receive buffer are provided to serve two functions. They enable the system clock to be modulated for communication with the repeater supervisory circuits without passing the modulation components beyond the system interface, and to reduce jitter. Associated with the former facility is a built-in 32 bit pattern generator which is essentially part of the submersible repeater monitoring equipment (SRME) function described later.

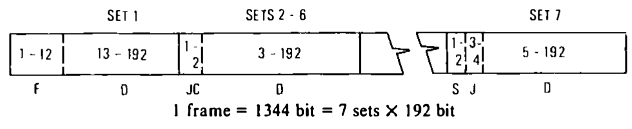
Laser Transmitter

The terminal electro-optics are the same as those used for the repeater so that a uniformly high system reliability is maintained. This is important when an unduplicated terminal equipment is used.

The basic control circuitry of the semiconductor laser is supplemented by additional circuitry to minimise the more variable environmental conditions found in a repeater station (unlike the relatively stable conditions of the sea bed). Peltier



(*a*) Tributary frame structure (141·888 Mbit/s)



(*b*) Common path frame structure (283·776 Mbit/s)

F: frame alignment word
D: data

JC: justification control digits
J: justification digits

S: service digit

Frame period = 4·736 μs

Fig. 5—NL1 system: Frame structure

semiconductor junctions† are used to actively regulate the laser to a stable temperature of 27 ± 1°C. This minimises mode hopping in the laser which would otherwise degrade the system dispersion penalty.

Receive Path

The processing in the receive path is largely complementary to the transmit. The principal differences are described.

Optical Receiver

The GaInAs PIN photodiode is followed by a high-impedance high-gain automatic gain control (AGC) amplifier which, together with internal control of the photodiode current, provides the required input sensitivity and dynamic range over the life of the system. Regeneration is carried out by a master-slave bistable driven by the 324·315 MHz clock extracted from the incoming signal via a surface-acoustic wave (SAW) filter.

A signal-level detector circuit is included which causes the AIS to be injected into both of the receive tributary outputs if the receive light level falls below a preset threshold.

At this stage, the system clock may contain modulation components from the repeater supervisory system. These are removed in a receive elastic store where the data is read in at the modulated 324·315 MHz clock rate and read out with a fixed frequency clock derived from the incoming clock via a phase-locked loop with a narrow pass band. The supervisory signal is detected by using a phase demodulator and passed to the SRME.

7B8B Decoder

The 7B8B decoder comprises a ROM with a complementary function to that of the encoder.

Before being passed to the decoder, the serial data is reassembled into parallel 8 bit words. An alignment circuit arbitrarily selects a phase of the incoming 8 bit word and detects the bit error ratio (BER). If the BER is greater than 1 in 10^3, the data stream is slipped one bit at a time until the BER is reduced to nominally zero, thus achieving alignment with the transmitted 8 bit word.

The error output from the decoder is connected to the error monitoring circuits described later.

Disinterleaver

After the decoder, the data is serialised and divided into two 141·888 MHz tributary paths. Each path contains one half of the complete FAW, each of which is unique to a tributary. FAW detect and interchange circuits ensure that the tributary contains the correct FAW and hence the correct traffic.

The same circuit detects frame alignment errors on the system and generates the frame timing and control signals for the ongoing decoding processes.

Receive Tributary

The signal is first descrambled in the tributary path. The descrambler is reset by the FAW to obtain synchronism with the scrambler at the transmit terminal. The remainder of the receive tributary provides dejustification of the data stream and removes the FAW and justification control bits. The resultant data is a complete replica of the incoming binary data and at the same rate.

Finally, the signal is re-coded with CMI for onward transmission over the repeater station distribution to the next line system or multiplex. The output is duplicated to provide a complementary service protection network function.

Engineering Speaker and Telemetry

A service digit is included in the bit stream of each tributary path (Fig. 5) and has an effective rate of approximately 211 kbit/s. This can be used for miscellaneous services such as telemetry and engineering speaker circuits between the two terminal stations.

Two standard 64 kbit/s A-law encoded pulse-code modulation (PCM) channels can be derived from either 211 kbit/s channel, and various interfaces added to provide local telephone facilities.

One channel on each SLTE can be replaced with a telemetry facility between terminals. This is primarily for exchanging terminal alarm conditions (those that can be transmitted through whatever fault condition has caused them). Typically, up to six alarms can be transmitted.

Operation and Maintenance

Maintenance Facilities

The transmission equipment has a number of in-built facilities for normal maintenance and fault location on both the terminal and the overall system.

The high bit rates used, together with the high level of integration in the main transmission paths, inhibit on-site location of faults to component level. The most effective repair technique is to locate a faulty card quickly and replace it with a spare. The faulty card can then be sent to a dedicated repair centre. The spare cards may, if required, be conveniently assembled as a complete spare and powered rack, which can also form a test bed for checking cards on site in their correct operating environment since the use of outriggers on the actual equipment can cause pulse timing and distortion problems which could mask the fault condition.

Most cards have clock and data test points to simplify fault location. The clock output can be used to drive test equipment to check the data for transmission faults or can be connected to an oscilloscope to check for correct characteristic conditions. Such tests may be carried out on certain test and monitor points whilst the system is still in service.

The alarm conditions provided on each SLTE have been chosen to localise clearly the fault to the system, and then to one of the terminals or the submersible plant. An SLTE fault can be located to a card and adjacent back plane wiring. A faulty card can be confirmed by substitution.

Error Monitoring

Single errors detected by the 7B8B decoder are buffered and fed to a monitor output for connection to external monitoring equipment. They are also fed to a counter which displays the error ratio on 7-segment displays from 1 in 10^8 to 1 in 10^3. Alarms are provided at a user-selectable threshold between 1 in 10^5 and 1 in 10^7 for in-station purposes, and the 1 in 10^3 output is permanently wired to a prompt alarm to indicate that the system should be taken out of service.

For this first system (UK–Belgium No. 5), where working experience of the effect of errors on network performance is required, the single error output is temporarily connected to more comprehensive error counting and analysis equipment designed by BTRL.

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† A Peltier junction is a semiconductor heat pump. When a current is passed through it, heat is transferred from one surface to the other thereby enabling it to actively cool or heat external devices.

Power-Feeding Equipment

The PFE for short-haul systems was designed from the outset with a duplicated plant at each terminal which can power the system as a single- or double-end feed arrangement. The maximum design output is 750 V, but is limited to a maximum of 20% above normal full system voltage. The line current is adjustable, but is nominally set to 1·55 A. This configuration, together with the use of the station DC supply as a power source, gives considerable security to system operation. A block diagram is shown in Fig. 6.

The need to terminate the bulky submarine cable, together with the large physical size and heat dissipation requirements of some power components, means that a different construction practice to the rest of the transmission equipment must be used. However, the overall dimensions of the equipment are constrained to that of normal repeater station rack and suite layout rules to ease the station planning process.

Power Units

Each power unit provides all the power-feeding requirements for one terminal. On short-haul systems, either of the two power units can power the system with the other acting as an interruption-free hot-transfer stand-by if required. On medium-haul systems, the two power units can also be connected to line together in order to share the load current.

One power unit also contains the dummy load used for the testing of either power unit or the complete suite when out-of-service. The other includes the high-voltage termination box for the submarine cable, fibre termination trays and the common control equipment.

Inverters

The inverter module forms the heart of each power unit and is used to convert the incoming 50 V DC to the high voltage (up to 250 V) DC output at 1·55 A. The system voltage is realised by the number and configuration of inverters used. One to three inverters can be employed for a single-end output of up to 750 V. The basic inverter design is similar to that used on the 45 MHz analogue systems.

The inverter operates at a frequency of 20 kHz to reduce the bulk of the magnetic components and reduce the sonic disturbance in the repeater station. Regulation is achieved by varying the pulse width of the input switching characteristic to vary the average AC input power to the step-up transformer. The regulation control is performed externally to this unit. The unit contains several built-in circuit functions to prevent incorrect or excessive output voltages being produced.

Alarms and Monitoring

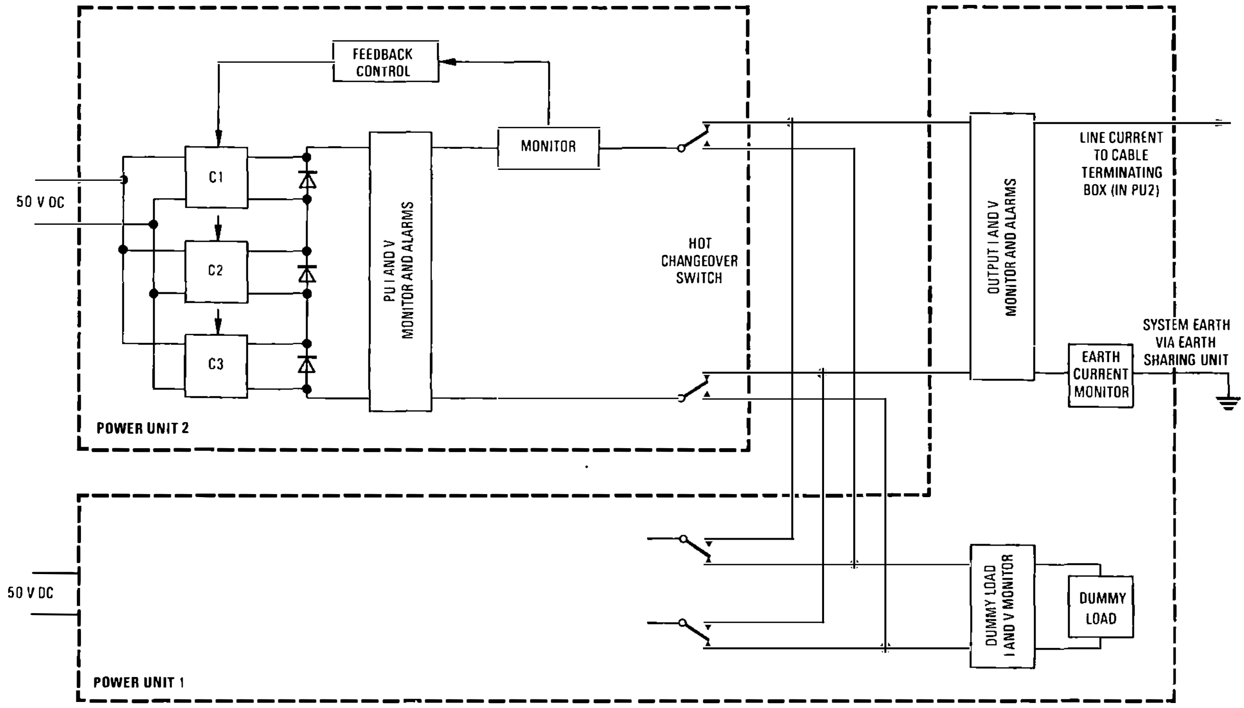
The various alarms from this equipment are classified into URGENT and NON-URGENT. Subsequent change-overs and other automatic or manual actions are controlled, initiated or prevented by this classification. Alarms indicating a 2% current and 10% voltage deviation serve to indicate abnormal but safe operation. A +20% voltage alarm will trigger an automatic shut-down of the PFE, but can be extended to +40% when adverse power-feeding conditions are expected on the system, typically when high voltages due to sunspot activity are induced into the cable.

Further alarms and interlocks are provided to prevent power units changing over when their differential voltage is excessive and to indicate failure or incorrect operation of the system earth used for power feeding.

Safety Features

The plant is fully interlocked to protect both personnel and the system from electrical and optical hazard.

The PFE suite at each terminal is mechanically interlocked to prevent access to high voltage areas. This is achieved with interlock keys which operate auxiliary switches to short-circuit high-voltage conductors as well as to prevent physical access. The key giving initial access to the interlock system is typically held by the officer responsible



C1–C3: DC–DC converter units

Fig. 6—NL1 system: power-feeding equipment

for power safety of the system in each terminal.

There is no easy means of extending the interlock system between terminal stations or from terminal station to repair ship, so a procedure of power safety messages and permits to work are operated. These procedures are mandatory and are further covered by the Health and Safety Regulations operating in the UK.

The lasers used in the system are Class 3b devices[4], which when viewed directly or indirectly are potentially dangerous. Under normal operating conditions, the design of the equipment is such that the system is intrinsically safe and therefore has been classified by the manufacturer as a *Class 1 System.*

An interlock system is provided between the SLTE and PFE to prevent access to the fibre terminating box (FTB) whilst the associated terminal laser is powered. The end-section optical attenuation prevents high optical levels from the submersible plant reaching the FTB under any powering condition, but a warning notice, careful siting of optical connectors and a key access system are provided nevertheless.

Submersible Repeater Monitoring Equipment

The SRME provides for in-service and out-of-service monitoring of the submersible plant and accommodates a data logger used elsewhere in the terminal equipment.

Equipment Configuration

The SRME (Fig. 7) consists of a single rack containing all the test and access facilities for the SLTE racks. The equipment comprises proprietary test instruments with computer control together with some dedicated circuitry for interfacing with the transmission paths.

A number of dedicated circuit boards provide the specific functions of the equipment including the access switches providing the data highway between the SRME and each SLTE. A standard computer with a built-in touch-sensitive screen for operator control and a floppy-disc drive for program and data storage, is used for instrument control via an IEEE 488 (IEC 625)† bus. An audio synthesiser for clock modulation is incorporated together with a BER measuring set for out-of-service tests at the 140 Mbit/s interfaces in each SLTE.

A suite of programs is provided to carry out the various tests with the SRME; a specific test is selected from a multiple-choice menu. The software is documented to enable the operating administrations to add peripheral control software to meet their own requirements such as to communicate with a mainframe computer monitoring several systems, should this be required.

An interlock is provided to prevent inadvertent selection of an out-of-service test on a system which is in service.

Test Facilities

The tests available from the SRME are listed in Table 1 and they are more fully described elsewhere[2].

TABLE 1

SRME Test Facilities

Test	Data Transmission	
	To Repeater	From Repeater
In-Service Laser health	FM on clock—level 1	Phase modulation of the received clock
Out-of-Service		
Received light level	FM on clock—level 2 32 bit word	Soft loop Loop off
Electrical loop-back	FM on clock—level 3	Hard loop
Error performance	FM on clock—level 3	Tester at 140 Mbit/s interface on SLTE

FM: Frequency modulation

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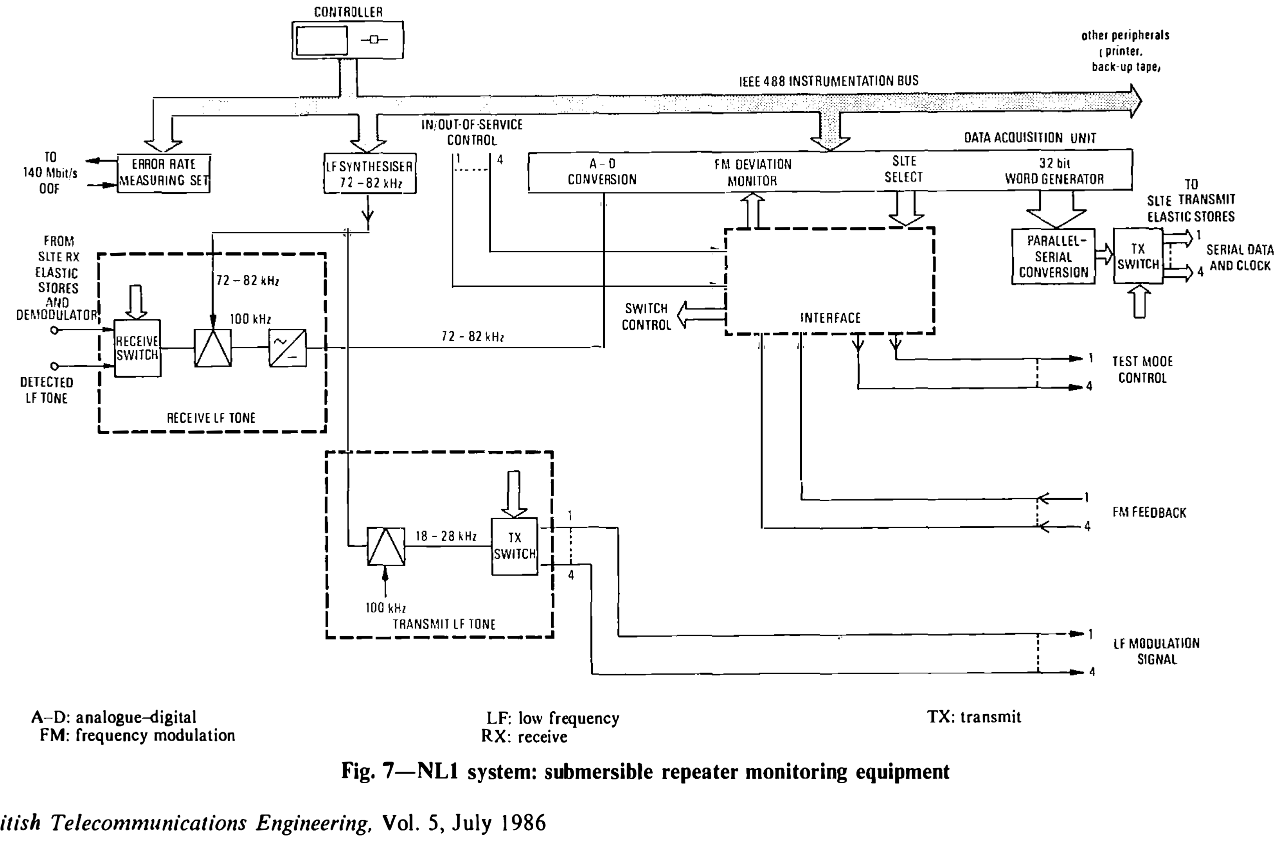
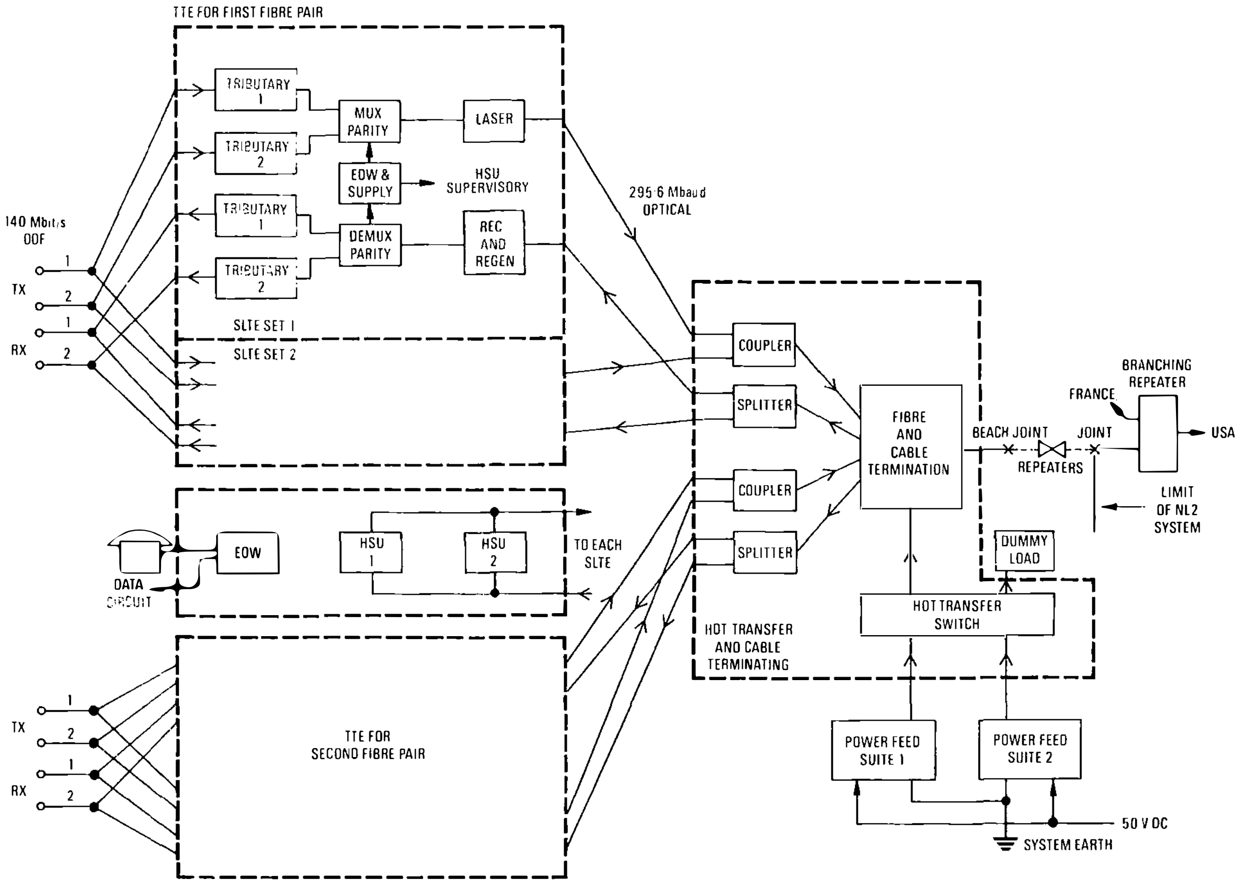
† IEEE 488/IEC 625 is an international standard interface bus for test equipment



A-D: analogue-digital
FM: frequency modulation
LF: low frequency
RX: receive
TX: transmit

Fig. 7—NL1 system: submersible repeater monitoring equipment



DEMUX: demultiplex
EOW: engineering order wire
HSU: home supervisory unit
MUX: multiplex
REC: receiver
REGEN: regenerator
RX: receive
TX: transmit

Fig. 8—NL2 system: TAT-8 terminal equipment

The SRME communicates with the repeaters by frequency modulating the system clock at up to 44 kHz, which is well inside the range of jitter tolerance correction that is provided in the receive terminal. The modulating frequency is within the range 18–28 kHz and defines the repeater, whereas the depth of modulation defines the type of command. Three levels of modulation are used:

Level 1 below the loop-back threshold for laser health measurement,

Level 2 provides a soft loop-back that can be overridden for received light level measurement, and

Level 3 provides a hard electrical loop-back that cannot be overridden.

The repeater responds for in-service tests by phase modulating the return clock and for out-of-service tests by looping the GO and RETURN paths within the regenerator pair.

THE TAT-8 SYSTEM

Common basic parameters were adopted for the TAT-8 system[5] following the decision to sub-divide the project between American, French and UK suppliers for the respective branches of the system. The suppliers were obliged to design compatible terminal equipments to a common standard.

This section concentrates on the principal design differences between the UK spur of TAT-8 (the NL2 system) and the short-haul terminal equipment already described. An overall block diagram of the terminal equipment is given in Fig. 8.

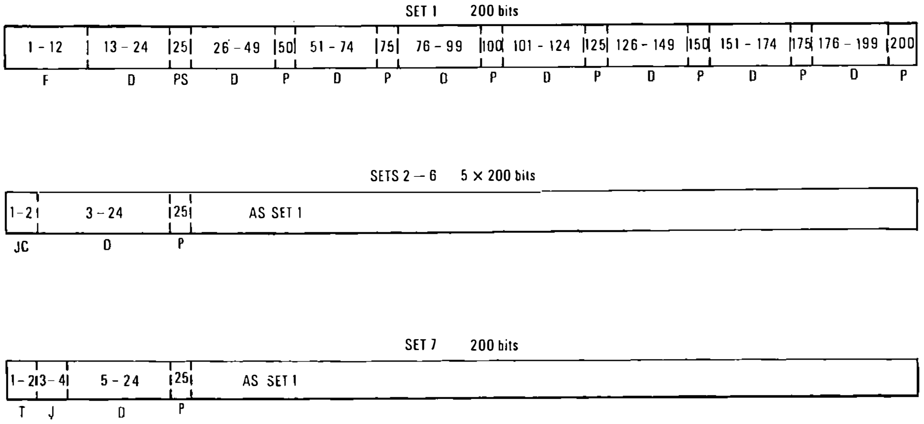
Terminal Transmission Equipment

The principal difference in the transmission method is the use of the unbounded 24B1P line code. The incoming tributary signal is justified and scrambled, increasing the data rate to 147·8 Mbit/s prior to interleaving. The 24B1P line coded signal is created by inserting an even mark parity bit in every 25 bit block, producing the line rate of 295·6 Mbit/s. A final frame size of 1400 bit is formed from seven sets of 200 bit (Fig. 9). Supervisory control and data channels for monitoring the repeaters and for passing system supervisory information between terminal stations is provided by causing controlled parity-bit violations in certain sets.

The strategic importance of the system in terms of network resilience required the terminal equipment to be fully duplicated to give it an availability more commensurate with that of the submersible plant. The two SLTEs are cross-connected so that it is possible to select any tributary input, multiplex or demultiplex and receiver or transmitter in any combination as shown in Fig. 10, with automatic changeover triggered by appropriate alarm conditions. Manual change-over is also possible for routine maintenance purposes. The terminal electro-optics are equivalent to a repeater, and transmit/receive pairs are connected to the single fibres by optical couplers (transmit) and splitters (receive). The stand-by laser is left unpowered in a similar way to those in the submerged repeaters to reduce ageing.

Power-Feeding Equipment

The system voltage and current depend on the number



1 frame = 1400 bit = 7 sets × 200 bit

Common frame structure (295·6 Mbit/s)

F: frame alignment word
*D: data
*JC: justification control digits

*J: justification digits
P: parity digit

PS: parity/supervisory digit
*T: telemetry digit

* Alternate digits from each tributary

Frame period = 3·383 μs

Fig. 9—NL2 system: frame structure

of repeaters and the regenerator configuration within the repeaters. The need to keep these parameters within reasonable bounds and common to all three repeater designs has resulted in a line current of 1·6 A giving a full system voltage of 13 kV. As this exceeds the rating of the capacitors in the repeater power separating path, the system must be double-end fed with the PFE at each terminal sharing the full system voltage.

The 'Y' configuration of the system complicates the power-feeding method both for system security and electrical safety. A requirement of the system is to re-established service in the unfailed branch and main cable after a single branch has failed. This facility is achieved by a relay switching matrix in the branching repeater and a controlled method of powering the system. The powering method is further complicated by having the branching repeater towards one end of the system thus preventing the main branch from being powered to full line current from the American terminal. The system is normally powered with the main branch and one spur double-end fed and the other spur single-end fed to a local earth at the branching repeater.

To power up the system, a low current is first fed from the spur designated to share the main branch load to an earth at the branching repeater; power is then gradually applied from the American terminal to configure the switching in the branching repeater. Power is then increased

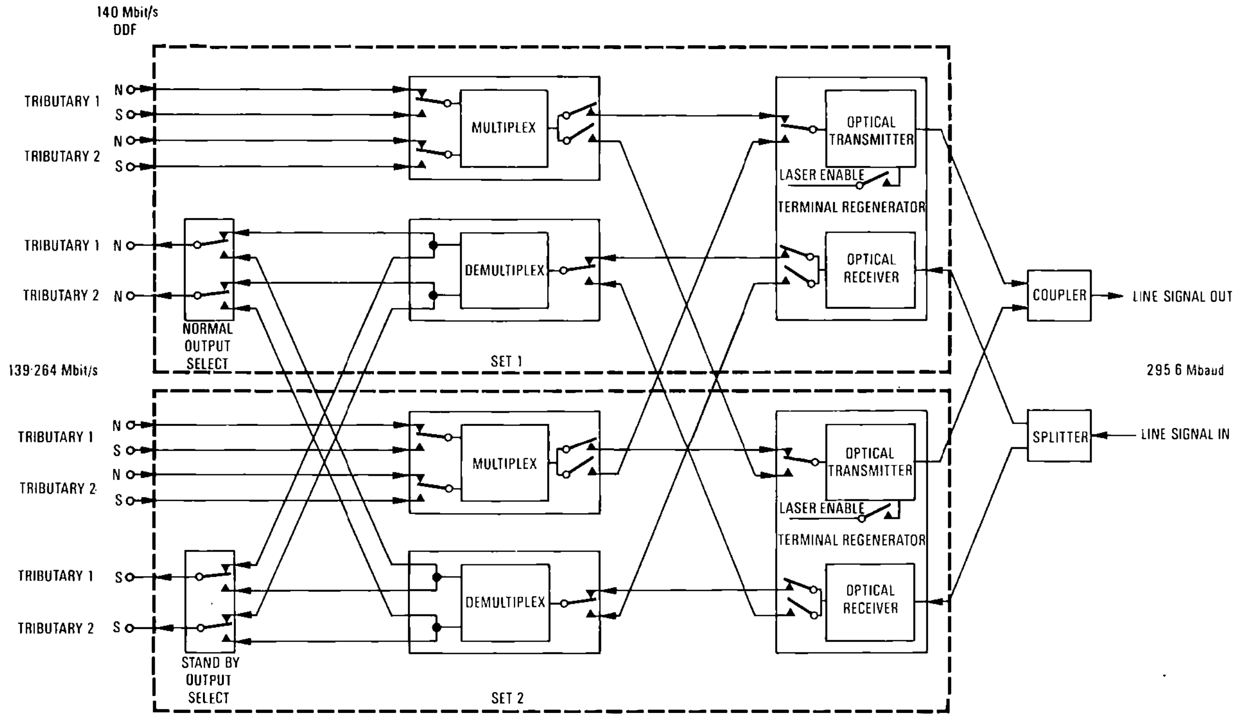
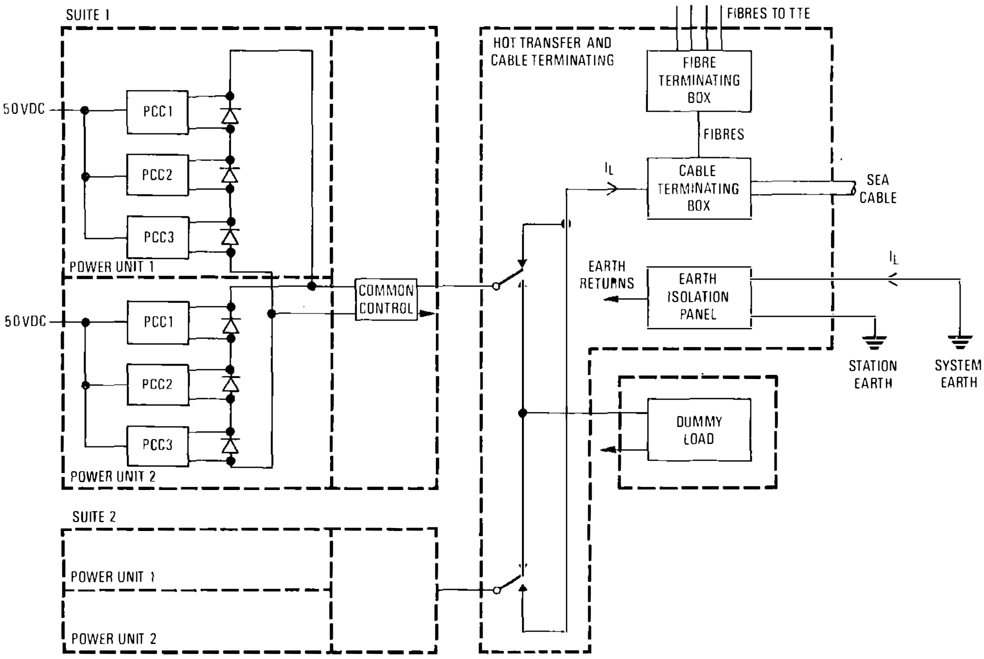


Fig. 10—NL2 system: submarine line terminal equipment duplication



PCC: Power converter cubicle, contains several DC–DC converters (1 PCC = 1 rack)

Note: Switching and earth returns omitted for clarity

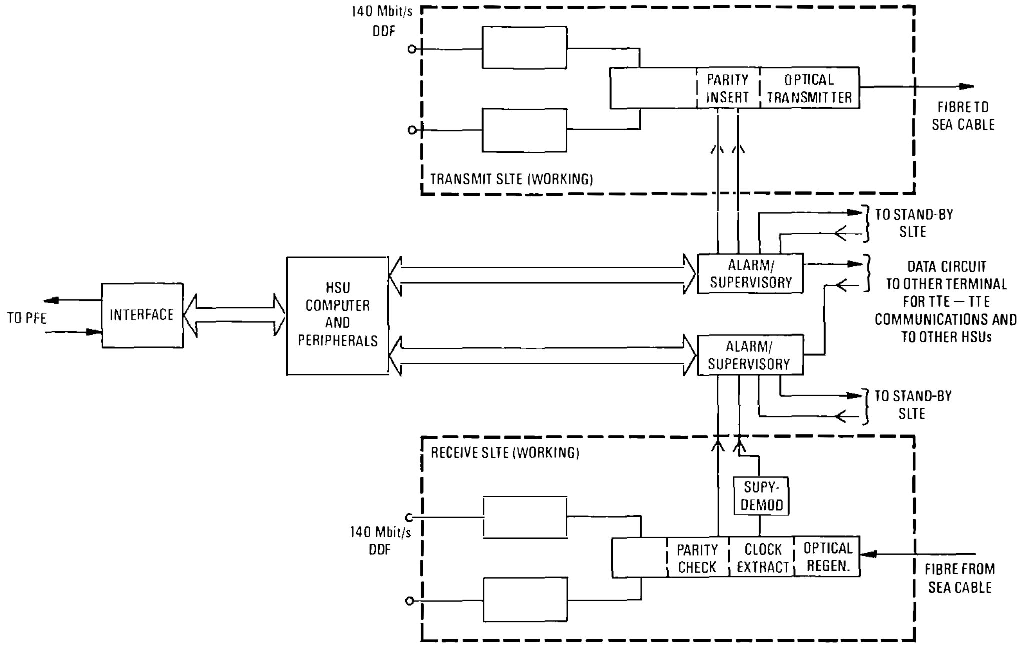
Fig. 11—NL2 system: power-feeding equipment

from both terminals until they both share the full load. Once the switching has been configured, the other spur can be powered independently to an earth at the branching repeater. If a cable fault occurs in one spur, up to 30 minutes of service interruption is allowed to depower, reconfigure and repower the fault-free part of the system, and leave the faulty spur free of power until a repair can be effected. Clearly, if the main branch fails, all service is lost.

As the system must be double-end fed with power, the equipment is effectively quadruplicated to provide the equivalent level of power security as with duplicated equipment on a system that can be single-end fed. Two main plants (Fig. 11) are connected via a hot transfer unit for interruption-free change-over enabling the stand-by plant to be worked on without removing the system from service. Each plant has duplicated power units working at the full terminal voltage and half the current. Either power unit can automatically take the full terminal load should the other fail.

System Supervisory Equipment

The requests for repeater supervisory information and the



Note: only one fibre pair shown for clarity

Fig. 12—NL2 system: home supervisory unit (HSU)

received data are handled by the home supervisory unit (HSU), which also controls change-over of the duplicated TTE, logging of alarms and exchange of information with the other terminals in America and France. The HSU is duplicated to maintain a high degree of reliability.

A common supervisory control is used for all regenerators in the UK spur so supervisory requests to and data from any regenerator can be transmitted and received on any fibre pair. The French and American supervisory systems differ from this and require access from both ends of the system. To accommodate these requirements, a remote supervisory unit (RSU), which can be patched into a defined interface, will be provided at the UK terminal by each of the other suppliers to gather supervisory information from their repeaters. Similarly a French RSU will be provided in America and an American RSU will be provided in France.

All HSUs are interconnected by conventional data circuits over engineering order wire (EOW) channels on the cable. Public switched telephone network backup is provided in the event of cable failure; a situation where the HSUs are in most demand for fault location. A block diagram of the HSU is given in Fig. 12. The HSUs also provide an automatic facility for locating and switching those faulty electro-optic components which are duplicated within the repeaters. A priority system has been set up to prevent interaction between the different supervisory systems.

CONCLUSIONS

The terminal equipments for short-haul and long-haul submarine systems have different design requirements and features. A first-generation short-haul equipment designed by UK industry has been described to demonstrate typical features required by operating administrations. Long-haul terminal equipment requires additional service security and is therefore duplicated. The first-generation equipment designed in the UK has been adapted specifically for the TAT-8 system to operate in conjunction with similar equipment designed in the USA and France.

The next generation of short-haul (up to 150 km) optical-fibre systems will be unrepeatered, requiring only terminal transmission equipment, but with more sensitive receivers and high-power lasers.

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Biography

After a Post Office apprenticeship and technician duties in the London East Telephone Area, Mr Myall transferred to Submarine Systems Division of Telecommunications Headquarters. He is currently Head of Group in the Satellite and Lines Executive of BTI responsible for submarine system terminal equipment and specifically for the implementation of the UK–Belgium No. 5 and UK–Denmark No. 4 optical-fibre submarine systems.

Quality Assurance of Submarine Cable Systems

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UDC 621.315.28 : 621.391.63

This article outlines the quality-assurance methods adopted by British Telecom International in all aspects involved in a submarine cable system project, including design, manufacture, installation and maintenance.

INTRODUCTION

This article describes the quality-assurance (QA) methods practised by British Telecom International (BTI) on submarine cable systems purchased by British Telecom (BT) and when BTI acts as a consultant for other international telecommunications authorities.

Quality is defined as: *conformance to the customer's requirement.* It follows therefore that the requirement must be clearly defined before conformance can be confirmed, and the customer satisfied. The customer/user requirement is given in detail elsewhere in this issue[1]. For the purpose of this article, the requirement can be described in general terms: submarine cable systems are expected to remain operational for at least 25 years. Their reliability should be such that component failures must not cause more than three repairs to the system throughout their long service life.

This is a stringent requirement for any advanced communication system, let alone one subjected to the hostile environment of the sea bed. To the ultimate customer, the international caller, such systems must offer modern communication facilities over networks that are reliable, available and affordable.

To ensure that the international caller receives the service required and to make certain that the product is fit for its intended purpose, an all-embracing control activity is necessary throughout every stage of the project. Such an activity is known as *quality assurance*, which is defined as: *all activities and functions concerned with the attainment of quality* (British Standard BS 4778).

BTI'S QUALITY POLICY

BTI's quality policy is to make the contractor responsible for meeting the defined quality requirements. However, because of the relatively-short warranty period compared with system life, and the high cost of repairs, BTI has decided on a policy of systematically monitoring the contractor's efforts in discharging this responsibility.

BTI'S QUALITY STRATEGY

The design, manufacture and installation phases of the contract are all the subject of monitoring by BTI. For this to be effectively achieved, a team effort is required. BTI's team comprises engineers from BTI, BT Research Laboratories and BT Quality Assurance. This brings together a comprehensive expertise in the design, development, manufacture, installation, maintenance and QA of submarine systems. This strategy has been in operation for many years and has proved to be successful and cost effective.

The costs associated with the supply and maintenance of submarine communication systems are considerable. Maintaining a system of inherent poor quality would increase these costs further.

QUALITY COSTS

Quality costs can be considered under two headings:

Failure Cost:	Costs resulting from poor control in the manufacturing unit.
	Cost of system maintenance and loss of service.
Prevention Costs:	Cost of implementing effective quality control procedures.

Taking either of the above to their ultimate limit would cost too much; the art is to strike an acceptable balance between the two.

SOME FINANCIAL CONSIDERATIONS FOR IMPLEMENTING A QUALITY-MANAGEMENT SYSTEM

Put simply, business is about meeting the customer's needs at a profit. Without either, or most probably both, of these features, there is no long-term future for a commercial enterprise. The eradication of defects is one important contribution towards meeting the customer's requirements of reliability, availability and affordability.

The most suitable method for ensuring output of the required quality is for management to decide.

Some options available are:

(*a*) no inspection of the product,
(*b*) 100% inspection,
(*c*) sample inspection,
(*d*) surveillance of quality-control procedures, or
(*e*) implementation of an effective quality-management system.

The objective in each case is the same: to find the most economic means of ensuring the customer's requirement.

Fig. 1 shows how the failure and prevention costs apply to the manufacturing situation. It is shown that, although the quality improvement adds to the basic system cost, the costs of poor quality are the most significant. For the system owner, the costs associated with ownership, that is, maintenance, need to be considered, see Fig. 2. Comparison of Figs. 1 and 2 shows that, when the ownership costs are considered, the preferred quality operating point moves to the right. This is associated with an increase in quality costs. These increased costs result from the implementation of more effective QA methods.

Before describing BTI's current QA methods, a brief outline of its past practice is given.

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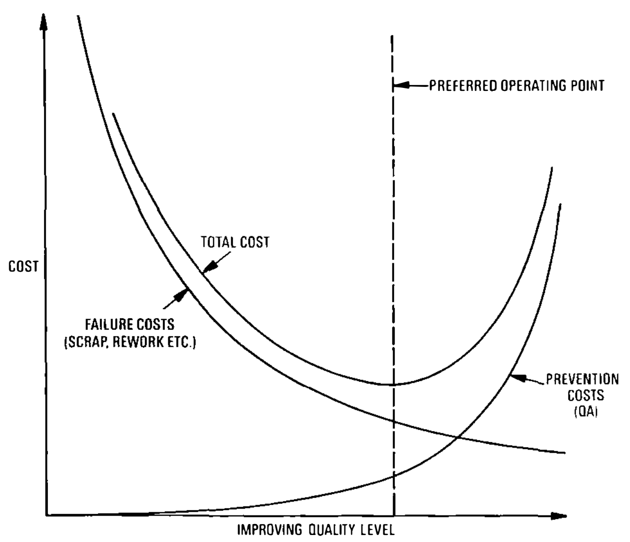
† Major Systems Procurement, British Telecom Development and Procurement



Reference: British Standard BS 6143

Fig. 1—Balance of failure and prevention costs in manufacturing

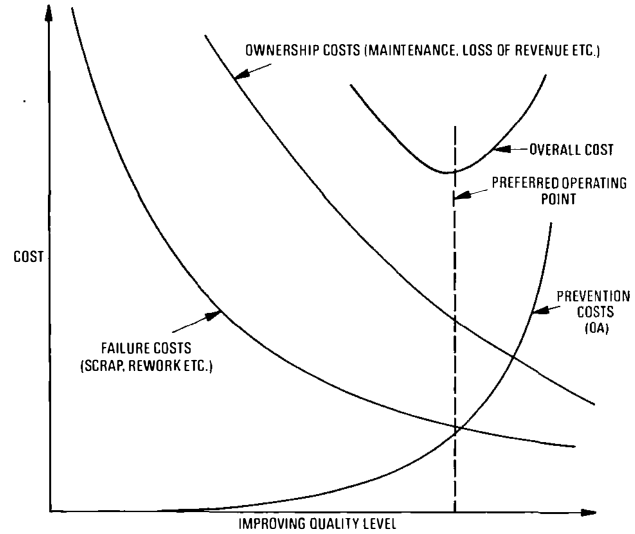


Fig. 2—As Fig. 1, but taking into account ownership costs

PAST PRACTICE

Historically, BTI's quality policy was to concentrate on the manufacturing phase of the contract; that is, inspection. Here a number of key stages were identified at the outset and the manufacturing/assembly processes were not allowed to progress until the BT inspector was confident that it was satisfactory to do so. This was known as *stop point inspection.* Although in quality terms this technique proved effective, it had several disadvantages:

(*a*) by approving the product/process in this way, the contractor could consider that it was relieved of part of its contractual responsibility;

(*b*) it required large numbers of experienced inspection staff who had to be available to meet the uneven production cycles of submarine cable systems; and

(*c*) it was costly to the customer.

Placing so much dependence on inspection has, in addition to those disadvantages listed above, another more significant shortcoming: inspection cannot of itself bring quality into an item. Too often, inspection alone merely sorts good from bad, and results in rejection and consequent costly scrap returns. Quality has to be designed and built into the product. Although inspection still forms an important part of BTI's QA activity, it is only a part. Today, much more effort is directed towards defect prevention; that is, 'to get it right first time'.

CURRENT PRACTICE

Earlier, it was stated that, to be effective, QA had to embrace all aspects of an activity. Fig. 3 shows how this applies to a typical BTI submarine cable system project. Here, several of the essential project elements are identified and the project manager is shown to be the focal point of them all. The QA function is shown to be all-embracing, having an influence on all activities, and not solely applied to manufacturing. Fig. 3 not only represents the modern BTI approach to project control, it also shows the preferred structure of the contractor's organisation; that is, the contractor's QA function has an input to all contract activities. An outline of how BTI operates project QA follows.

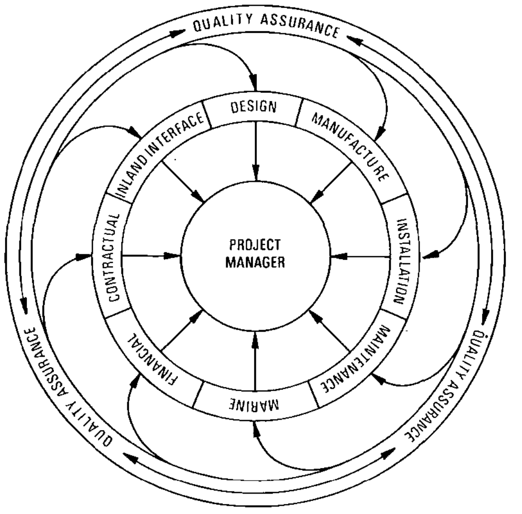


Fig. 3—The role of QA a typical submarine cable system project

All projects have three distinct phases:

(*a*) pre-contact,
(*b*) in-contract, and
(*c*) post-contract.

These three are now considered in sequence.

PRE-CONTRACT QA

The pre-contract activity broadly described indicates how and when the QA aspects are considered in the preparation for contract placement; that is, it is aimed at the prevention of problems likely to affect the reliability, availability and affordability criteria.

Invitation to Tender

When the invitation-to-tender document is prepared, the system quality requirements have to be accurately specified and written into the tender.

Quality Requirements (Contract Condition)

In addition to the stated quality requirements of a system, which are covered in the technical specification, the contractor is now required to give a description of the quality-management system (QMS) used.

QMS can be defined as: *the system of management for all quality-related matters*. Such a system is required to show how the contractor ensures that the product conforms to the contract. A system based on BS 5750 Part 1 or an equivalent national standard is expected.

BS 5750, which is titled *Quality Systems*, describes the minimum requirements necessary for an acceptable quality system. It is a general specification and is not specific to submarine cable system manufacture. BS 5750 Part 1 is used to specify the system of QA necessary to ensure that the required quality standards are achieved and maintained. It applies when the design, manufacture and installation functions are ultimately the responsibility of the contractor. Reliability and other characteristics can be ensured only by the effective control of quality throughout all phases of this work.

Additionally, when submitting a tender, the contractor is required to include a copy of the company's quality manual and a typical quality plan. These will then become part of the contract and therefore legally binding.

The quality manual sets out the company's general quality policy, its procedures and practices, while the quality plan sets out the specific quality practices, resources and activities relevant to the particular contract. Fig. 4 shows the hierarchical structure of these documents.

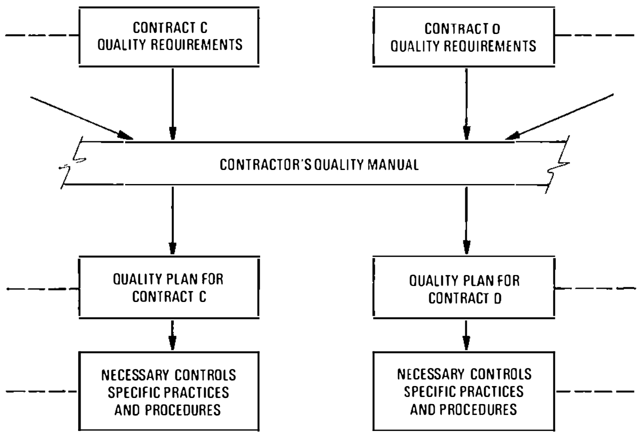


Fig. 4—Hierarchical structure of contract quality documents

The quality manual is a document common to all contracts. The quality plan is project based, and details the specific requirements for that project. The quality plan results from negotiations between the contractor and the project manager. Once agreed, the quality plan becomes part of the contract and must not be altered without the project manager's agreement.

Adjudication of Tenders

Part of the tender adjudication is concerned with an assessment of the submission on quality; for example, the quality manual and quality plan. Since the quality requirements are carefully stated in the invitations, the initial paper assessment is straightforward. Does the contractor's quality submission comply? If not, what are the probable implications of the stated non-compliances? Serious non-compliance at this stage could lead to disqualification. A fully complying submission supported by an acceptable quality manual and quality plan is, at least, a step in the right direction. If available, any current knowledge of the contractor's quality systems is also taken into consideration. The next essential step, before the contract is placed, is to assess the potential contractor's manufacturing capability and the effectiveness of the contractor's quality-control procedures; that is, a vendor appraisal.

Vendor Appraisal

The vendor appraisal is necessary to verify that the quality-management system declared does indeed comply and that it is being effectively applied; that is, whether the system gives confidence that only an acceptable product is manufactured for release to the customer. Only after this on-site assessment has taken place, and the conclusions carefully considered, should a recommendation be made.

IN-CONTRACT QA

Verification of the contractor's quality arrangements by the purchasing authority is best achieved by thorough monitoring of the contractor's activities. This activity is triggered once the contract has been placed. The first step for the contractor is system design.

At the forefront of the designer's brief is the customer requirement; for example, the system must be reliable, available and affordable. These is no point in designing and then manufacturing something that the customer does not want.

QA IN DESIGN

The advent of optical-fibre technology and its application to submarine cable systems meant that most of the proven designs associated with coaxial systems were no longer appropriate. However, requirements for maintainability and reliability remain; for example, no more than three ship repairs because of component failure in the expected 25-year life of the system. These, together with a need for a reduction in the cost per circuit, set the designers a formidable task, and they carry the reponsibility for the quality of their designs. The application of quality-management disciplines is aimed at ensuring that the product complies with these requirements.

To determine that the design QA procedures are in place and are effective, quality audits are made of the design team's operation. Fig. 5 summarises design QA audit activities and outlines typical audit areas.

Concept of Quality Audit

Quality auditing is a non-executive function, as distinct from operations such as inspection and surveillance (performed for the sole purpose of product acceptance or process control), which involve making decisions for action, although quality auditing can involve the review of these functions.

Quality auditing can relate to the quality of a product, a process or an activity; it is carried out on a periodic basis and involves the independent and systematic examination of actions that influence quality. The object is to determine whether the quality system complies with the agreed documentation; for example, quality manual, quality plan, specifications, procedures etc. It should also appraise their suitability.

QUALITY OF DESIGN

Quality of design is verified by either type tests or qualification tests, both possibly leading to type approval. These terms can be described as follows:

Type Test A test or series of tests directed towards the approval of a design, and conducted to determine whether an item is capable of meeting the requirements of the product specification.

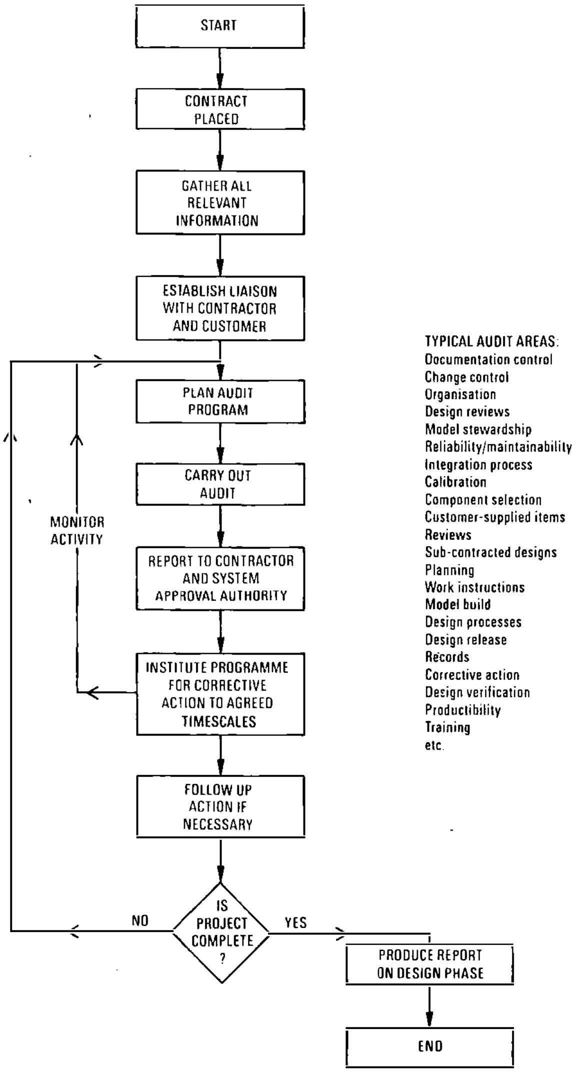


Fig. 5—Typical audit procedure for the design activity

Qualification Test A test or series of tests directed towards establishing the competence of the manufacturer to produce the item.

Type Approval The status given to a design that has been shown by a series of type tests and/or qualification tests to meet all of the requirements of the product specification and which is suitable for the specific application.

Where purchase is from a UK contractor, BTI is the approval authority. In the case of an overseas contractor, BTI requires comprehensive evidence of a satisfactory test programme.

Generally, type tests are carried out on cable and the associated elements. Qualification tests are more commonly associated with the repeater and its associated components.

Elements attracting type approval are typically:

REPEATER:
- Capacitors
- Crystals
- Diodes
- PINFETS
- Integrated circuits
- Lasers
- Thick-film substrates
- Transistors
- Protection devices
- etc.

CABLE:
- Optical fibres
- Fibre splicing
- King-wire welds
- Pressure-tube welds
- Land section cable
- Armoured shallow-water cable
- Cable terminations
- Various joints
- Armoured cable repair
- etc.

All of the qualification tests and ideally the type approval programme are completed and approved prior to the manufacture of the actual system components, although this may not always be possible when long-term reliability studies are involved. Examples of this are the laser and PINFET devices used in optical systems; here the results of detailed reliability calculations and predictions are taken into consideration. Of course, as with any product employing new technology and new manufacturing techniques, much of the approval programme is based on detailed predictions. Where possible and practical, trials are held to prove and support these predictions. One such trial was that commenced in Loch Fyne in February 1980[2, 3]. This was the world's first trial of a submarine optical-fibre system. Here, 10 km of submarine optical-fibre cable was laid to a depth of 100–150 m. Originally, this cable was unrepeatered but included an empty repeater housing. This empty sea case was later replaced with a housed multimode regenerator. System performance was monitored jointly by the contractor and customer. The outcome of this trial, so far, is one of mixed fortunes. For the trial to have been a complete success would have verified the designers theories at least in as far as the system was truly representative of an actual in-service system, and in this regard the system has its shortcomings. In practice, the trial revealed a number of design limitations, thus proving the usefulness of such a trial, and the need for a comprehensive quality-management approach. The intelligence gathered from this trial led to changes in design that have since been proved to satisfy fully the design objectives and hence the customer's requirements.

QA IN MANUFACTURE

The objective of QA in manufacture is to ensure that those standards, techniques and disciplines common to the production of the 'qualified' samples are maintained throughout the manufacturing cycle of the system. Again, this is wholly the contractor's responsibility and success in achieving this relies heavily on the integrity of the contractor's quality organisation.

Contractors have been very active in improving their QA techniques and in developing greater quality consciousness themselves and in their subcontractors. BTI has acknowledged this improvement in quality awareness, and has responded by a change in its approach when monitoring a contractor's activity. Today, for the UK contractor at least, 100% inspection is generally unnecessary, and quality-audit techniques are used; this results in considerable cost savings for the customer. The contractor also benefits since, because stop point inspection is removed, operations can be carried out at the contractor's own pace.

These savings have been made possible as a result of the pre-contract activity, where strict quality requirements were placed on the contractor; that is, the contractor was required to demonstrate that effective QA procedures were being carried out, as detailed in the quality manual and quality plan.

As mentioned earlier, the high cost of system failure, both in terms of repair-ship time and lost revenue, leads most purchasing authorities to conclude that the contractor's activity must still be supported and monitored by their own quality organisations.

To be effective, the authority's own organisation has to work to an agreed quality plan, as this provides the key to the surveillance and monitoring procedures practised by them.

The authority's quality plan is drawn up after careful consideration of the contractor's plan and, although designed to cover the entire manufacturing process (plus design, installation and maintenance), it may, if considered necessary, concentrate on some specific areas. Normally, it would involve auditing of the management function, manufacturing/assembly processes and inspection of the product.

Typically, this audit would investigate the effectiveness of the requirements listed in Table 1 (from BS 5750 Part 1) as they apply to the particular activity being audited. The procedure for auditing the manufacturing activity is shown in Fig. 6.

TABLE 1
Quality Requirements

Quality system
Organisation
Review of quality system
Planning
Work instructions
Records
Corrective action
Documentation and change control
Control of inspection, measuring and test equipment
Control of purchased material and services
Manufacturing control
Purchaser supplied material
Completed item inspection and test
Sampling procedures
Control of non-conforming material
Indication of inspection status
Protection and preservation of product quality
Training

The contractor's quality plan outlines his test strategy throughout all stages of manufacture with particular emphasis on the final acceptance tests. In cases where the purchasing authority considers that the contractor's test programme is sufficiently comprehensive, then it becomes the subject of an audit. At present, BTI verifies the contractor's results for itself and carries out its own tests.

It must be emphasised that quality audits are not a substitute for acceptance testing.

The advent of optical-fibre technology to submarine systems has meant changes from the traditional strategy for acceptance testing. With coaxial systems, a variety of technical and practical reasons precluded the assembly of the system prior to the actual laying operation. With optical systems, it is now possible and practical to assemble the system in the factory and to make provisional acceptance tests prior to loading the system onto the laying vessel.

Progress in the Application of BS 5750 to Submarine Systems

The British Standard BS 5750 was first published in 1979 and, although it has had an impact on the QA of submarine cable systems, it has still to be fully applied across the entire activity. Installation and maintenance, although using effective quality-control procedures, still have to be fully aligned to it; that is, the requirements listed in Table 1 have to be applied as appropriate.

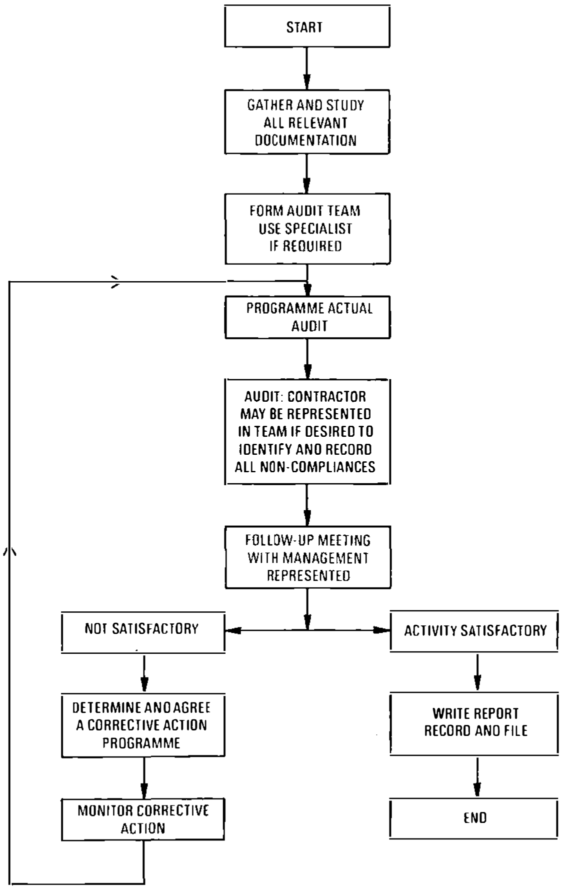


Fig. 6—Typical audit procedure for the manufacturing activity

QA in installation and maintenance as currently practised is now described.

QA IN INSTALLATION

The two main aspects of installation are:

(*a*) submerged plant—cable and repeaters; and

(*b*) dry-land-based plant—terminal station and associated equipment.

Submerged Plant Installation

As with the design and manufacture, the contractor has the overall responsibility for installation. BTI monitors this activity.

The contractor's shipboard duties are considerably reduced when laying optical-fibre cable systems as there is no longer the need to design and build the equalisation networks essential to coaxial systems. However, all of the marine and some, albeit modified, transmission test requirements remain. The contractor details plans for the load and laying operation in the system load and laying instruction (SLLI). This is subject to the approval of the project manager and must be strictly followed. The customer's own shipboard QA representative(s) monitor both the technical and marine aspects of the laying activity to ensure that the system is satisfactorily installed.

Some examples of the details provided or made reference to in the SLLI are:

(*a*) a responsibilities table—who does what;

(*b*) all necessary safety precautions and procedures;

(*c*) conditions for safe stowage of the system throughout the loading when in transit and laying;

(*d*) details of all transmission tests;
(*e*) preferred cable route details and survey information;
(*f*) details of the ship's navigation aids and its calibration status;
(*g*) details of the ship's cable laying instrumentation and its calibration status;
(*h*) provision of necessary jointing equipment;
(*i*) provision of spare plant;
(*j*) procedures and work instructions where necessary;
(*k*) qualification status of jointing engineers;
(*l*) operation of, and precautions necessary for, power-feed equipment; and
(*m*) procedures to be followed when initial and final splices are made.

In addition to the above, a comprehensive log giving such details as the actual route of the laid cable and the control of the cable slack is required. This and other relevant information must be recorded in an up-to-date incident report log.

Dry-Land-Based Plant Installation

The terminal station building and the installation of the necessary apparatus are overseen by BTI personnel, who adopt a 'Clerk of Works' role. Building plans and equipment layout drawings are produced and the work is done in accordance with the associated instructions. Once the transmission test and power-feed equipment is installed, acceptance tests are made by both the contractor and the customer's representative. Land work, external to the terminal station, for example, the provision of cable ducts, the laying of the land section cable and cable jointing, is often carried out by BTI's own staff under subcontract to the contractor.

The installation of the transmission and power-feed equipment is programmed so that it can be used to monitor the performance of the main-sea section of the cable once the initial splice has been made and laying is underway. This monitoring is done by both the contractor's staff and the customer's representative throughout the lay until the final splice is complete.

Once the system has been installed, comprehensive commissioning tests are made by both parties. Results of the tests made, records of problems encountered and their solutions are fed back to the design authority for future reference.

Reference measurements are made of the system performance and recorded to assist in future maintenance operations.

POST-CONTRACT QA

QA in Maintenance

The responsibility for the maintenance of the system changes as the various contract milestones are reached. Initially, the responsibility is with the contractor, but it is eventually transferred to the system owner/operator.

To enable the maintenance and fault rectification activity to be effectively controlled, the precise areas of responsibility must be established. Once these areas of responsibility are identified, the quality requirements listed in Table 1 should be applied. Some typical areas for specific consideration are:

(*a*) disposition and stock of maintenance equipment, in storage depots and on board service vessels;
(*b*) arrangements for preserving the product in storage depots and on board service vessels;
(*c*) test strategy and procedures for terminal, land and submerged plant faults;
(*d*) provision of and operational instructions for fault location equipment used on board service vessels, in terminal stations and field work;

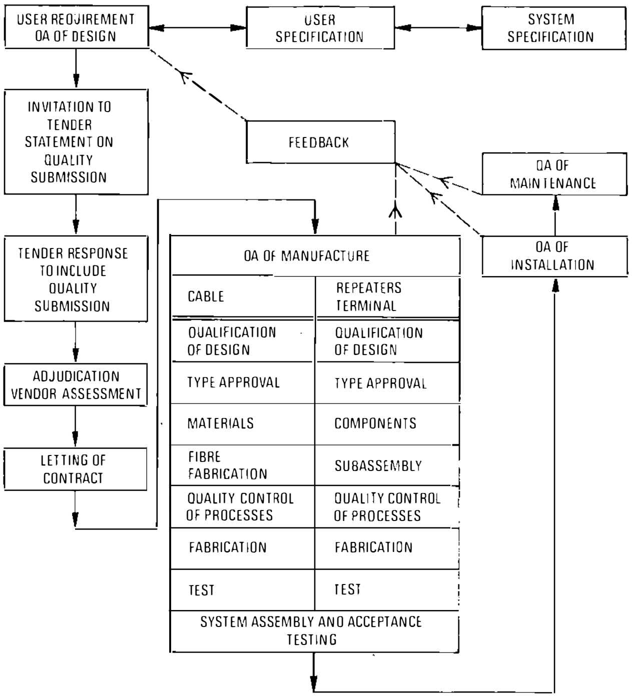


Fig. 7—The QA loop

(*e*) provision of and instructions for the use of repair kits;
(*f*) facilities for the repair of recovered plant;
(*g*) repair techniques and work procedures; and
(*h*) training of staff.

The feedback of defect details is the final link in the QA chain. It closes the loop in the all-embracing activity (shown in Fig. 7) necessary to ensure customer satisfaction.

SUMMARY

This article has outlined the QA methods adopted by BTI for the provision and maintenance of a submarine cable system. The high cost of ownership, for example, the maintenance and repair costs, make it essential to direct effort towards failure prevention; that is, 'to get it right first time'. The initial and most vital step is to have a statement of quality requirements written into the invitation-to-tender documents. The role of BTI QA is then to ensure that the contractor complies with those requirements.

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Biography

Alan Williams is BT-QA Client Manager to BTI. He joined BT in 1959 as a Youth-in-Training in the then Test and Inspection Department. After an initial training period, he spent several years on QA in the works of major suppliers to BT of power-feed equipment. He then specialised in electrical measurements and was directly involved in the development of BT's Electrical Standards Laboratory. He is an approved British Calibration Service signatory for electrical measurements. After a short spell on the QA of land cable systems, including the 60 MHz coaxial link, he transferred to submarine system work. He has worked on many international projects. The ANZCAN system gave him the opportunity to work in Australia for nine months, where he was the system co-owners' representative in the repeater assembly plant.

Protection and Installation Techniques for Buried Submarine Cables

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UDC 621.315.28 : 621.391.63

This article discusses the desirability of burying undersea cables to protect them from damage, and goes on to describe equipment that enables this operation to be carried out economically; namely, British Telecom International's plough and Submersible Trencher.

INTRODUCTION

In the early-1980s, British Telecom International (BTI) undertook a major review of its cable protection philosophy. This was necessary because cable routes were being subjected to increasing damage from trawlers, which was attributed mostly to increased trawler size and lifting capacities. Initially, BTI's response was to develop trawler-resistant cables by increasing the amount of armouring. This policy, together with the abandonment of low-capacity low-strength cables, has significantly reduced the number of fault incidents. At the same time, and in particular with the dawn of the optical era, investigations into methods of providing even better and cheaper protection were initiated.

As a result of these investigations, a decision to bury cable whenever it was practical or economic was taken. This meant that cable designs and cable laying and recovery methods had to be reappraised, and new techniques developed to meet this new challenge.

DEPTH OF BURIAL

A literature search*, confirmed by practical tests conducted at British Telecom Research Laboratories, Martlesham Heath, showed that, to provide protection from anchors, cables would need to be buried to 2–2·5 m. Clearly, this would be very difficult to achieve and would have required a massive development programme. In addition, further tests conducted at different sites in Britain showed that the cable would have to be very strong if it was ever to be retrieved from such buried depths. Analysis of fault reports showed that cable damage arises mostly out of trawl damage. Tests conducted with beam trawls showed that relatively little cover is needed to give protection. Ship sizes and anchor sizes were studied before a compromise of 600 mm was chosen as the optimum depth of burial. This depth gives good protection against trawlers, reasonable protection against anchor damage and does not impose excessive demands on the strength of cable to enable it to be recovered from the sea bed without breakage should a repair be necessary.

INSTALLATION

A study of all the existing installation techniques was undertaken. To ensure the maximum cost saving on cable design, and to minimise the risk of damage during the installation period, it emerged that burying the cable as it was laid was the most desirable solution.

Of all the available methods, the ship-towed plough looked to be the most economic. However, existing ploughs left the cable in an open trench and this feature was particularly undesirable around Britain where undulating sea beds made the possibility of unburied suspensions highly likely.

The cable ships also experienced difficulty in handling the large heavy ploughs during launch and recovery, and normally used divers during these parts of the operation. This put a severe limitation on the sea state in which ploughing could be commenced, and often meant that for recovery operations the ship had to seek sheltered waters with the plough hanging beneath the stern.

NEW PLOUGH DESIGN

The study of existing ploughing and handling techniques resulted in the development of a unique design of plough (Fig. 1) (developed by BTI and jointly owned with the Danish Posts and Telegraphs) that cuts a thin wedge of soil (Fig. 2) and places the cable beneath it.

The cutting action is achieved by a vertical share blade preceded by a cutting disc set at 35° to the vertical. The soil wedge is gently lifted up and sideways by a ramp fitted at the base of the share while a depressor arm pushes the cable down within the plough body. As the plough progresses along, the wedge of soil flows past the plough and back down the trench on top of the cable. This gives immediate cover and protection to the cable and holds it down in areas of undulating sea bed.

During sea trials on the plough, divers were deployed to verify the depth of burial. They reported that the cable was fully buried with the sea bed reinstated within a metre of the plough, little evidence of the trench was seen on the sea bed.

Another unique feature is that the plough can be steered independently of the ship by ±15° from the ship's course. It is steered on the sea bed by rendering on one or other of its bridle legs. This facility enables it to avoid rocks, to steer into troughs in sand-wave areas and to control the amount of slack being introduced into the buried cable by tacking at preset distances.

The plough can bury cables ranging in size from 25–140 mm outside diameter and can pass repeaters up to 360 mm outside diameter. Its burial depth can be varied from 0–0·9 m by controlling the position of the front skids, and its rate of burial can be up to 4 km/h. The plough's weight is less than 10 tonnes and, when coupled to its efficient soil cutting design, results in a machine that requires only a low towing force (10–20 tonnes) in typical sea beds.

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† Marine Services, British Telecom International

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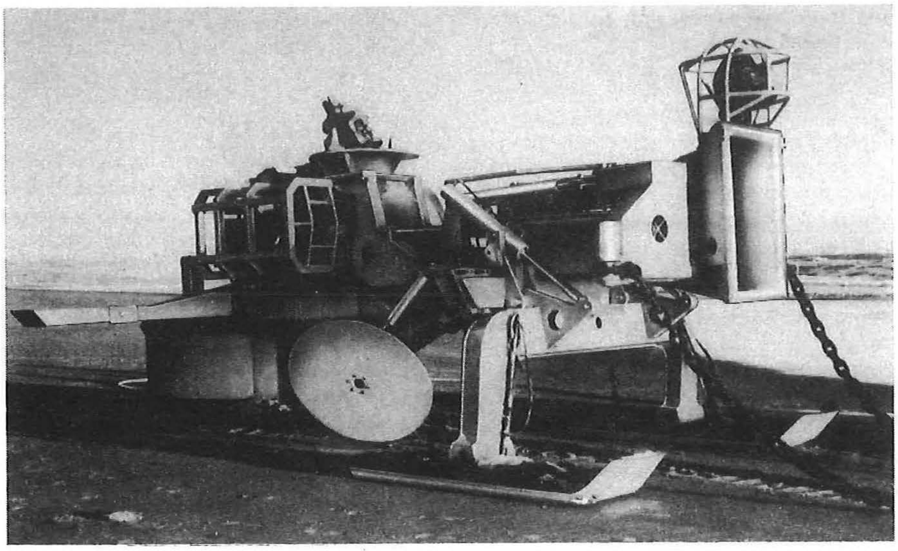
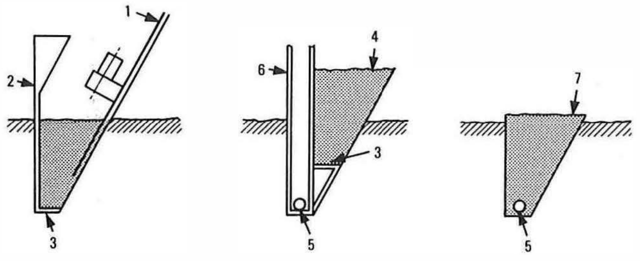


Fig. 1—BTI plough



1 Inclined cutting disc
2 Vertical share blade
3 Ramp to lift soil wedge
4 Soil wedge
5 Submarine cable
6 Cable slot in plough body
7 Soil wedge reinstated on top of cable

Fig. 2—Cross-sections through the furrow slice before, during and after the passage of the cable burial plough

The plough is equipped with three video cameras, two mounted on pan-and-tilt units and one in a fixed position. These, together with the 100 m range sonar and a host of position, depth of burial and load sensors and inclinometers, enable the operators to monitor and record the cable burial operation.

THE GUIDE TUBE PHILOSOPHY

One of the essential parameters that enable successful cable burial to take place is the control of the cable tension as it enters and leaves the plough. Research established that the residual tension left in the buried cable should not exceed 2 tonnes to prevent it from unburying itself in a sand-wave area. This meant that the cable had to be laid at a low tension in front of the plough to take account of the frictional losses on the cable passing through it. It was decided to develop a 'guide tube' system to support the cable from the ship to the plough.

The guide tube system consists of a series of plastic mouldings that attach to the towing wire at intervals and allow the cable and repeaters to slide down it at low tension. The plough's umbilical cable is also attached to the guide tubes, leaving only one catenary to control between the ship and the plough. This simplifies the overall control of the plough system during cable burial.

SHIP MODIFICATIONS AND PLOUGH HANDLING SYSTEM

Extensive modifications to the cable ship *CS Alert* were needed to install a handling and towing system for the plough. It was decided that the handling system should not require the assistance of divers during launch or recovery and that the plough should not be able to swing freely as it was lifted over the after deck.

The system that was designed is based on an 'A' frame with a telescopic leg and recovery winch suspended from its cross beam. The leg extends down and locks onto the plough on the deck, lifts it up and then over the stern, lowering it close to the water before releasing it. The whole system is hydraulically operated and damped to counteract the pitch and roll of the ship. The plough can be both launched and recovered to the ship with the cable in it without the need for stopper ropes to restrain the cable. The system is suitable for operating up to sea state 6 in open seas.

Other modifications to the ship included a new ship's control room overlooking the aft deck and mounting positions for the umbilical winch and plough control container. Deck extensions around the aft deck were made for additional storage areas for the guide tubes and a small deck crane.

SEA TRIALS

The ship and plough system underwent a successful sea trial in May/June 1985.

At the end of July 1985, 18·5 km of optical-fibre cable were buried by the plough from the Danish cable ship *CS Peter Faber* across the Great Belt from Nyborg and Halsskov.

Towards the end of April 1986, 88 km of optical-fibre cable was buried between the UK and Belgium. The sea bed included chalk, clay, sand and sand-wave areas. Later, the plough will be used to bury the UK section of TAT-8 and the UK–Denmark No. 4 optical-fibre cable systems.

OPERATION FROM OTHER VESSELS

Although the plough was originally designed to be operated from the *CS Alert* or *CS Peter Faber*, the system is transportable and can be operated from any suitably equipped vessel.

The essential features required of the mother ship are good manoeuvrability and position keeping, together with adequate deck space and a bollard pull in excess of 50 tonnes.

The equipment required for plough operation consists of a handling system or crane capable of plough deployment, a self rendering towing winch set to 50 tonnes and suitable navigation equipment for the area.

REBURIAL AFTER REPAIR OPERATIONS

Although the plough is designed to receive and release cable without the need for cutting and jointing, it is not suitable for burying the final splice of a submarine system. Neither is it economic to use a plough to bury the relatively short lengths of cable inserted into a system after repair operations. The BTI Submersible Trencher was designed not only to uncover buried cables for fault location and recovery purposes, but also to jet a trench alongside surface-laid cable into which it can then be lowered.

BTI TRENCHER

The BTI Trencher, Fig. 3, is a remotely-controlled submersible which can be operated from any suitable vessel via a portable containerised control cabin. Although the submersible weighs 1600 kg in air, launch and recovery is possible up to sea state 5 by a custom-built portable 'A' frame which is readily installed on to the chosen mother ship.

The Trencher is capable of penetrating the sea bed up to 1 m, with its powerful combination of fluidisation jets and dredge pump, in water depths between 3·5 and 300 m. Its endurance on the sea bed is limited only by the station-keeping capabilities of the support vessel.

The Trencher has four horizontal and three vertical thrusters which enable it to swim freely to the work site, to avoid obstructions on the sea bed and to undertake inspections. It has variable buoyancy ranging from +400 kg to −1800 kg and, once locked on to the cable through its magnetic and tone location systems, the track drive with differential steering can follow the cable automatically.

The 64 mm diameter composite umbilical cable provides 1000 V 50 Hz three-phase power supplies to the vehicle and comprehensive monitoring facilities, including video systems. Gripper units and heavy duty hydraulic cable cutters attached to the Trencher's manipulator arm facilitate the removal and connection of ropes during repair operations.

CONCLUSIONS

Together, the BTI cable ships, plough and Trencher provide a comprehensive facility for the complete protection of submarine cable systems by burial in the sea bed. Armouring costs on future systems will be substantially reduced, the reputation of submarine cable for high reliability will be further enhanced and, not least important, trawlermen will have fewer sea-bed obstructions on which to snag their gear.

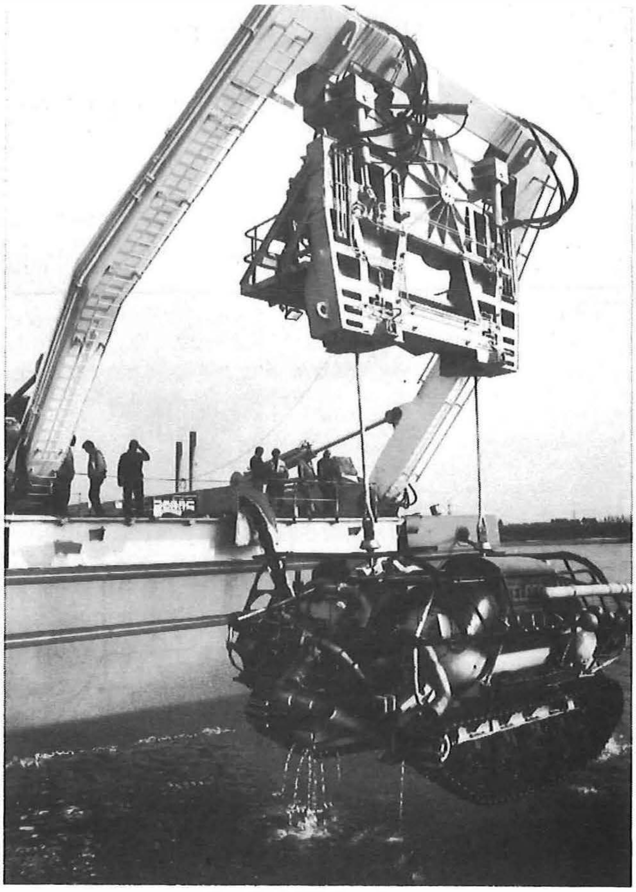


Fig. 3—BTI Trencher

Biographies

Chris Cole joined the then Post Office in 1973, after some nine years with the Mechanical and Civil Engineering Department at the Department of Transport, Hendon. He worked on mechanical development and the testing of hydraulic systems for external telecommunications plant, and then, in 1979, joined BTI, overseeing maintenance, design and development of cabling machinery onboard *CS Alert* and in the cable depot. He has been British Telecom's representative on the commissioning of the SCARAB submersible and adviser on the technical committee for the system. He has also worked as project manager for the design and procurement of portable handling equipment for the BTI Trencher, and for the development, procurement and operation of the submarine cable plough and its associated handling and towing system for *CS Alert*.

Robert Struzyna is a technical manager responsible for BTI's fleet of three ships. He studied Mechanical Engineering at City University, London, after spending a year in New Guinea on Voluntary Service Overseas. He joined the Post Office Structural Engineering Group in 1971, working on the design of radio masts and towers and, in 1974, moved to Marine Division to undertake mechanical development arising from the introduction of high-capacity submarine cables. In 1980, he moved to British Telecom Research Laboratories to lead the Hydrospace Engineering Group, which pioneered many of the techniques now being adopted for the burial and repair of optical cable systems.

UK–Belgium No. 5

Part 1—Marine Aspects of the Route Selection

R. WHITTINGTON†

UDC 621.315.28 : 621.391.63

The UK–Belgium No. 5, the first international repeatered optical-fibre submarine cable system, was laid earlier this year across the southern North Sea. This article, the first of two, describes the work undertaken to select a suitable route so that the cable could be buried to protect it from mechanical damage. The second article will describe the technical aspects of the system and its installation.

INTRODUCTION

Owners of submarine cable systems make determined efforts to ensure that their systems operate without risk of interruption and the consequent need to undertake costly repairs by cable ships.

Most failures of submarine cable systems are caused by mechanical damage. A large percentage of the faults can be attributed to the fishing industry and particularly to those vessels engaged in bottom trawling.

Over the years, in order to minimise this risk, submarine cable owners and manufacturers have worked together to design better protection, generally in the form of improved armouring to the cable.

Unfortunately, these improvements in armouring have been matched by the fishing industry's coincidental development of larger, heavier and deeper beam trawls in its own search for greater efficiency and reward. Consequently, in recent years, more attention has been directed towards cable burial as a method of protection.

Burial of submarine cables beneath the sea bed has always been an attractive form of protection, but the design of efficient tools for this purpose has only recently been achieved. For such tools to work effectively, it is essential for the operating area to be carefully selected.

This article reviews the work undertaken by British Telecom International (BTI) Marine Services to select the shortest most-suitable route for the UK–Belgium No. 5 submarine optical-fibre cable, taking account of the requirement to maximise the distance which could be buried.

INITIAL ROUTE PLANNING

Once the landing points for the system had been declared, and found acceptable to all concerned, initial planning commenced by studying navigation charts (typically British Admiralty charts) and associated publications (see Fig. 1). In particular, it was necessary to find a suitable route through the mass of heavily fished sandbanks in the southern North Sea to ensure that the UK–Belgium No. 5 cable could be safely laid and repaired by the available cable ships.

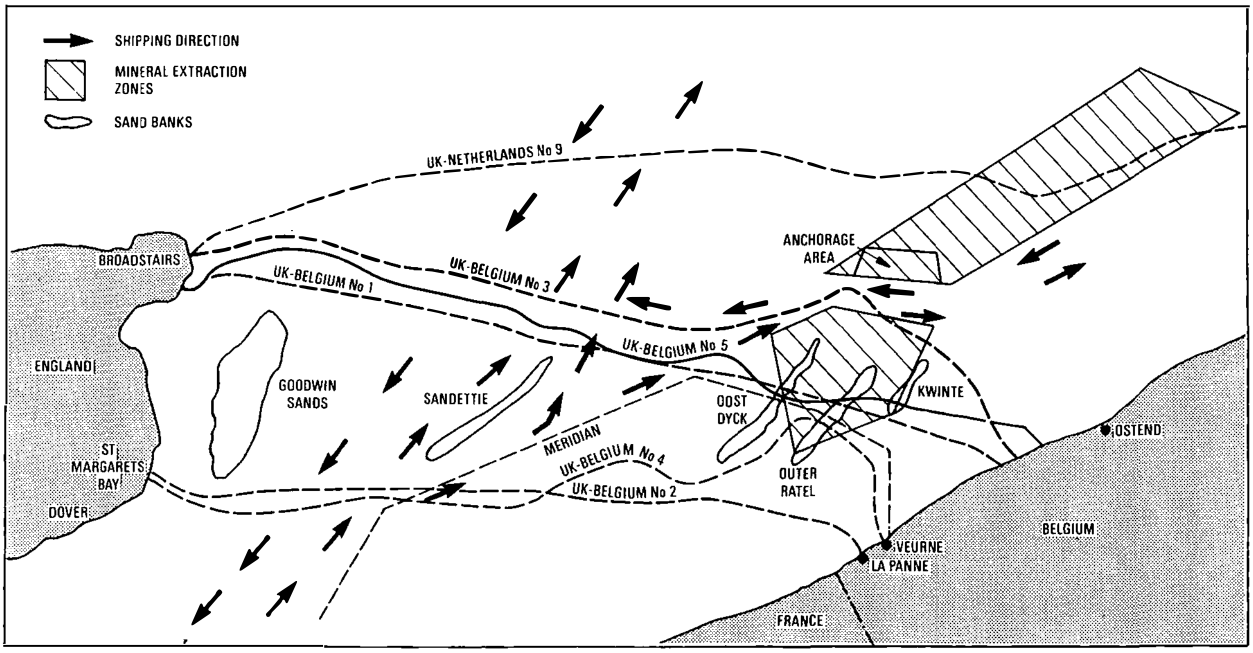


Fig. 1—Simplified chart showing route of cable

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† Marine Services, British Telecom International

As their name implies, navigation charts are intended primarily to facilitate safe surface navigation. Although not infallible, they show those features which positively assist the mariner and indicate known hazards that prudent navigators would avoid.

Navigation charts are prepared, produced and updated with freely-exchanged information between international Hydrographic Offices.

Hydrographic surveying is costly and time consuming so effort is generally concentrated on those areas which form the main 'through-ways' for shipping. Although navigation charts include little data of direct value to the sea-bed user, there is still a wealth of invaluable information to be gleaned by the submarine-cable planner concerning areas which should be avoided. Consequently, navigation charts (readily available at relatively low cost) form the initial worksheets.

A preliminary route which takes recognition of all the currently identified features that might be prejudicial either to the cable or to its installation can be plotted on the charts. These features will include:

(*a*) wrecks,
(*b*) sea marks (navigation buoys, lightships etc.),
(*c*) anchorage areas,
(*d*) traffic separation zones,
(*e*) sand banks and shallow waters,
(*f*) rugged contouring, and
(*g*) areas of sea-bed instability or seismic activity,

all of which pose some degree of threat to a submarine cable, whether buried or not.

Once the preliminary route is selected, the planner can undertake further investigation with various local and national government departments to establish whether or not other sea-bed users have a mutual interest. These will include commercial companies that:

(*a*) are licensed to recover sea-bed material for the construction industry,
(*b*) are licensed to dump spoil at sea,
(*c*) will be undertaking hydrocarbon exploration and exploitation, or
(*d*) propose to undertake civil engineering activities.

Additionally, during this intelligence gathering phase, any aspects relating to national or international legislation current or proposed which may have some impact on the operation are taken into account.

The Ministry of Defence Hydrographic Department has always been a valuable source of information relating to wrecks, and holds details of some 20 000 wrecks off NW Europe. Much of this data is old, and cannot be regarded as completely reliable. For example, not all the 'positions' of the many ships lost during the Second World War can be confirmed. Efforts were undertaken to disperse wreckage from navigable channels by explosives so as to give a safe depth to the area, but this merely resulted in the wreckage being spread over a wider area. What might be safe for surface navigation could prove to be quite unsuitable for laying and burying a submarine cable.

No matter how comprehensive, navigation charts and intelligence gathering alone cannot provide all the information needed to confidently select a practical route. For this, a physical survey is required.

GENERAL OBJECTIVES OF THE PHYSICAL ROUTE SURVEY

The route survey is required to determine the configuration of the sea bed relative to a common vertical datum, sea level, and to identify any natural or artificial bottom features.

All data acquired about the vertical datum has to be related to the horizontal position.

The route survey will confirm:

(*a*) the depth of water, submarine contours and particularly any steep slopes,
(*b*) the nature of the sea bed and features such as rock outcrops and sand waves,
(*c*) the sub-bottom strata and geology down to 2 m,
(*d*) sediment erosion in the form of scar trails and depressions,
(*e*) the existence of any wrecks or obstructions, and
(*f*) previous fishing activity indicated by trawl scars on the sea bed.

All of this is undertaken by using ship-borne instruments giving mobility and flexibility. All measurements made in the vertical plane depend on acoustic reflections from boundaries between different types of material. The operational frequency and power of the equipment used will determine the degree of resolution.

Survey Equipment

Echo sounding allows accurate vertical measurements from the transmitter to the surface of the sea bed.

Side-scan sonar equipment produces a record of the sea bed similar to an aerial photograph. The equipment would normally be able to define rocks, sediment types, wrecks, obstructions and other sea bed anomalies.

Sub-bottom profiling equipment is used to map the soft surficial sediment and identify its thickness and composition.

Positioning

It is obviously important to know the precise position of the survey ship so that the laying ship can accurately reproduce the same location. Every endeavour is made to keep errors to a minimum by using suitable position-fixing equipment so as to achieve the greatest accuracy.

Positional control is best achieved in the marine environment by electronic position-fixing systems. There are many different systems available to meet a wide range of criteria. Microwave systems give the greatest accuracy, but are limited in their range. Low-frequency systems have enormous range, but the accuracy suffers. Medium-frequency equipment gives the best compromise, with good range and adequate accuracy.

Unlike survey work on shore, position fixing during a route survey is less accurate if for no other reason than the ship from which it is conducted is dynamic, and repetition of observations to reduce errors is impracticable. An accuracy in horizontal control of better than 1 m is seldom required at sea and is rarely obtainable. At a distance of 50 km or more from the shore, accuracies of 10–20 m are considered good.

Mariners, professional or recreational, use the well-established internationally recognised geographical co-ordinate system using latitude and longitude. Surveyors, marine or land based, use conventional grid systems. Marine planners have to use both systems. Hydrographic surveying requires an interface to the adjacent land mass. The topography appearing on navigation charts is usually obtained from the appropriate land-survey authorities. In the case of British Admiralty charts for UK waters, this is based on the Ordnance Survey Datum. For the UK–Belgium No. 5 sea route, the navigational charts used were based on the European Datum (1950) and the Ordnance Survey Datum. The differences are significant only when large scales are used.

To overcome these problems, marine surveying is frequently undertaken by using the Universal Transverse Mercator (UTM) grid system. Also, most position-fixing equipments used for surveys express positions in grid co-ordinates. Thus errors are reduced because no attempt is made to convert from one co-ordinate system to another.

ROUTE SURVEY OF UK–BELGIUM No. 5

Organisation

The contract for the final route survey of UK–Belgium No. 5 was placed with the British surveying company, Wimpol Ltd., of Swindon. The company used the motor ship *Tugro*, a converted Dutch coaster, for the work.

Apart from the ship's regular crew, Wimpol supplied a team comprising surveyors, geophysicists and engineers to operate the survey equipment and evaluate the results on board. Two representatives from Marine Services attended the survey enabling surveying to be undertaken on a 24-hour basis.

Equipment Used

Navigation

Navigational positions were provided by the Racal-Decca Noordzee HiFix 6 chain operating in the 1·6–3·4 MHz range. This uses transmitter stations at Deal, Thorpeness, Texel and Renesse to provide four overlapping hyperbolic radio beams enabling accurate position fixing to be obtained. Although absolute accuracies of 1–30 m are claimed for this system, more significant is the specified repeatability (that is, ability to return to the same point) of 10–15 m. This is particularly useful in avoiding detected obstacles. The receiver was interfaced to a desk-top navigation computer.

Echo Sounding

An Atlas-Deso 20 precision echo sounder was used on board the survey vessel to obtain bathymetric (depth) information on all the survey lines. To correlate depth with position, fix marks were passed from the navigational computer to the echo sounder and presented graphically along with the bathymetric data on an integral dry-paper recorder. The echo sounder was connected to hull-mounted transducers operating at 33 and 210 kHz simultaneously. This had the advantage of providing a means of distinguishing between sea-bed material types as well as providing an accurate profile of the sea bed.

Sea Floor Mapping

In order to obtain a graphic representation of the sea floor along the survey corridor, a side-scan sonar towfish was used, connected to an EG&G Sea Floor Mapping System (SMS). The towfish produces acoustic signals from a pair of 105 kHz transducers which are reflected off the sea bed to produce an image of its surface. The SMS has the advantage over conventional side-scan recorders in that data is corrected for slant range and is automatically adjusted for the vessel's speed to produce a true picture of the sea floor. The data was recorded in true plan form and real time on an integral dry-paper recorder as well as being recorded on magnetic tape.

Sub-Bottom Profiling

To investigate the shallow geology of the sea bed and to ascertain the surficial sediment thickness, an Ocean Research Establishment (ORE) pinger system was utilised. A towfish, incorporating an array of four transducers operating at selectable frequencies from 3·5 to 8 kHz, was connected to a compatible transceiver and the results displayed on a dry-paper recorder. At these low frequencies, some penetration of the sea bed by the acoustic signal is possible. The reflection from layers within the sea bed indicates their structure.

Bottom Sampling

In addition, to confirm the results described above and to ascertain the nature of the sea bed and its suitability for ploughing, a grab unit of about 40 000 cm^3 with a hinged bucket was used.

DISCUSSION OF RESULTS OBTAINED

General

The overall results were very comprehensive and the details are best depicted in graphical form on the appropriate survey charts. However, a résumé of the findings is given.

Echo Sounding

Three sounding lines were carried out along the major portion of the proposed route (centre line and 200 m either side). Additional lines were undertaken across the Kwinte, Outer Ratel and Oost Dyck Banks (Fig. 1). All soundings obtained were corrected for the effects of tides by reducing the results to the standard datum known as *Lowest Astronomical Tide* by using predicted tidal data for Margate and Dunkirk. The results showed prominent sand-wave areas on the sea bed having characteristics ranging from 5 m amplitude/70 m wavelength to 13 m amplitude/300 m wavelength.

Sea Floor Mapping System

The data obtained from the SMS was generally of good quality except in the very shallow water areas (less than 10 m) where the signals were sometimes corrupted by a combination of weather conditions and vessel noise. (Owing to the short tow cable necessary in shallow water, vessel movement is transferred directly to the towfish via the cable, and cavitation from the propeller causes false reflections and noise. In deeper water, a larger length of cable is used and, consequently, vessel noise is more remote and the movement is damped, or absorbed, by the cable.) No artificial hazards or bottom debris were identified during the survey. In some areas, scarring of the sea bed by trawlers was detected. The orientation of the sand waves was clearly determined and in some cases their direction of movement, denoted by relatively steep lee faces, was very pronounced.

Bottom Sampling

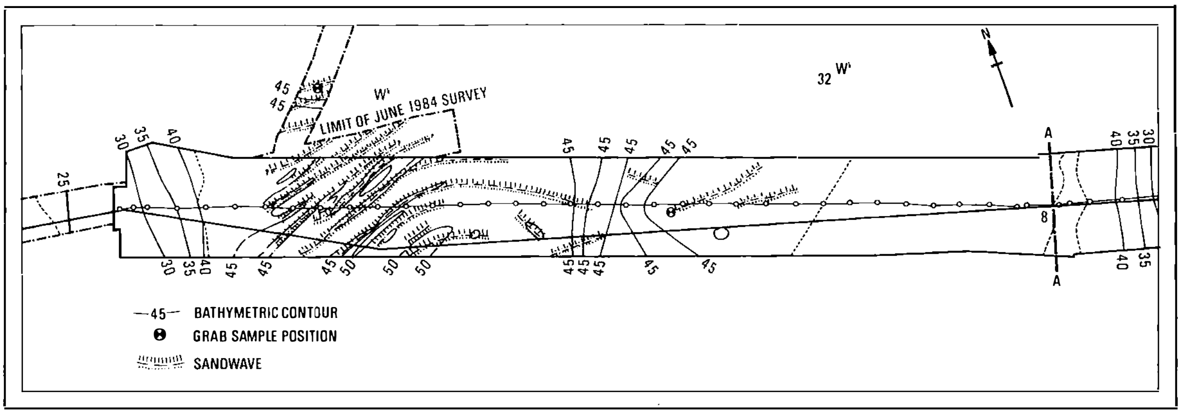
The samples from this exercise were sealed in plastic bags for further analysis. Samples were taken at eight locations.

Profiling

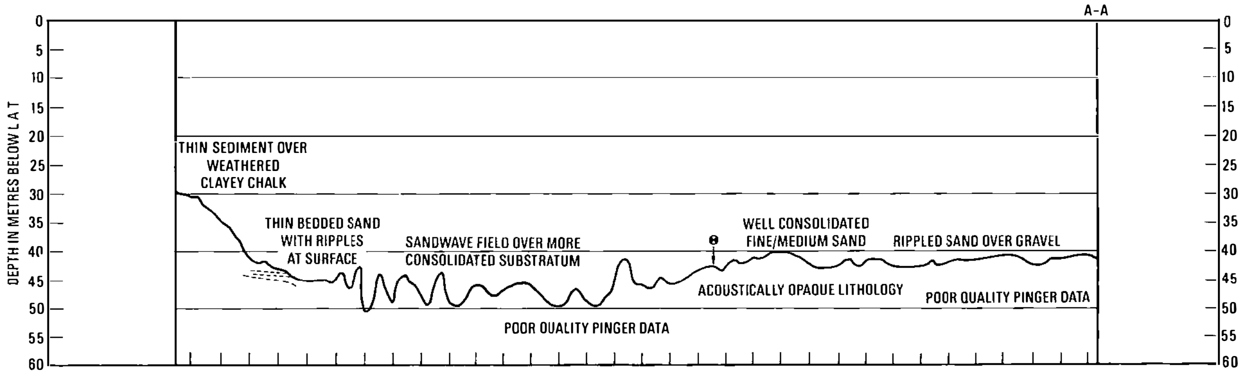
The quality of the records obtained was variable and latterly a poor performance was reported. Consequently, comprehensive information was not obtained. Even so, it was possible to determine the stratification to some degree.

POST SURVEY WORK

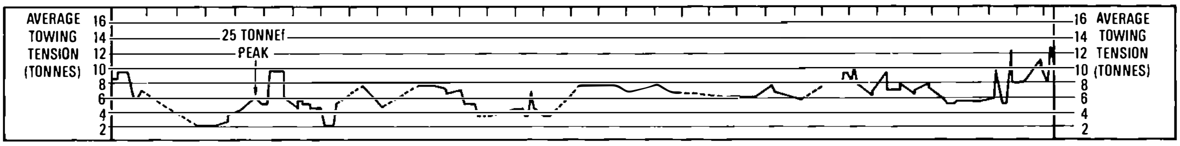
As part of the contract, Wimpol produced survey charts to a scale of 1:10 000. The information supplied was novel to BTI Marine Services in that it was depicted in strip form showing both plan and side views on cable alignment and route survey sheets. These were produced by carefully appraising all the information acquired in the field and repro-



(*a*) Track plot



(*b*) Sea-bed profile



(*c*) Average towing tension

Fig. 2—Cable alignment and route survey profiles

ducing the data in perspective to the correct scale (see Fig. 2).

The detail portrayed on these route alignment sheets permitted more accurate planning to be undertaken. Routes were drawn to avoid undesirable features and the appropriate alter-course positions noted. Altogether, there were 26 alter-course positions. These were essential to avoid the principal features of concern; namely, sand waves.

In their most simplified form, sand waves are areas of heaped sand transported by the net tidal effect, with their axes transverse to the mean tidal direction. Unfortunately, the axes and the mean direction of the cable lay were not coincidental.

Because the sand waves along the route appeared to be mobile, it was essential that the route was planned so that the cable could be laid/ploughed through the troughs. Then, in the event of any migration occurring, there was a good possibility that the cable would receive further protective cover by the sand waves covering the buried cable.

The survey results across the Oost Dyck, Outer Ratel and Kwinte Banks were not encouraging. From the earlier studies of the navigation charts, it was recognised that there might be difficulties in finding sufficient depth of water for the cable ship to cross safely. In the event a route was found, but it did mean that passage had to occur on a rising tide, close to high water. The implication was that in this area the cable ship would not be able to plough in the cable because the speed of advance during ploughing would be too low. The chosen alternative was to surface lay across the banks and to improve the protection of the cable in this area by increasing the armouring.

POST SURVEY OPERATIONS

General

The route survey had not detected any artificial sea-bed hazards, but this did not prove that the route was clear. There was still the possibility of marine debris being present in the form of wires, chains, fishing gear etc., jettisoned or lost from passing vessels. These hazards would all have a low profile above the sea bed or be covered to some degree by the sediment. Non-detection during the survey did not preclude their presence and some positive form of route clearance was necessary.

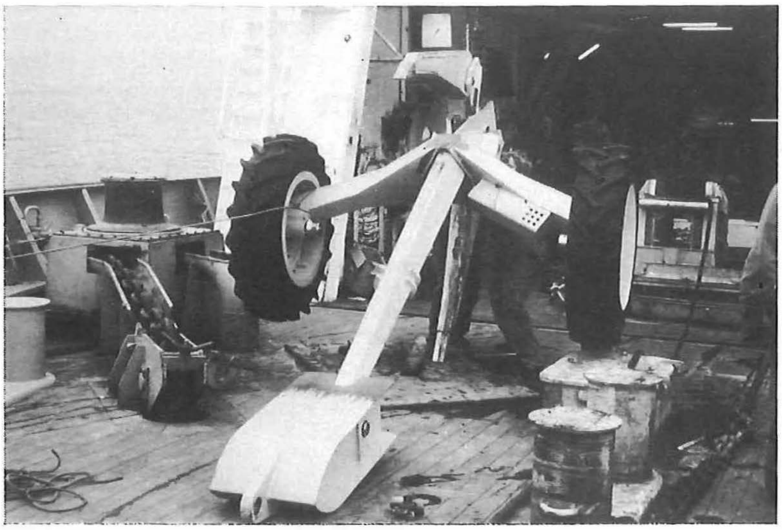


Fig. 3—The BTI detrenching grapnel

Route Clearance

The BTI detrenching grapnel (Fig. 3) was designed to recover purposely or naturally buried submarine cables. This grapnel, which has a penetration of 0·7 m compared with the plough, which is 0·6 m, therefore makes it an ideal tool for assessing the ploughability of the route as well as clearing debris.

When grappling for submarine cables, engagement is usually determined by a rise in the towing tension. However, as the detrenching grapnel penetrates so deeply into the sea bed, the towing tensions could be very high and erratic, depending on the type of sea bed, to such an extent that any engagement is masked by these high tensions.

To assist in determining that debris had been hooked, a sensor was fitted to the grapnel. The sensor was activated by debris which rides along the grapnel fluke triggering off an acoustic device which can be detected by the ship.

Plough Performance Assessment

Research by British Telecom Research Laboratories (BTRL) had shown that there was likely to be good correlation between the towing force of the detrenching grapnel and the plough in various types of sediment. By analysing recorded towing tensions and the ship's speed, the probable performance of the plough could be predicted for the route (see Fig. 2). The information relating to expected towing tensions and speed of advance would then allow the plough team to be prepared for such changes during the installation phase.

The presence of consolidated material or bed rock could cause the plough to ride out and thereby reduce the effective amount of cover. A ride-out sensor was fitted to the grapnel so that such events could be detected.

The abrasive nature of the sea-bed material was not known. It was unlikely, but possible, that the plough share could suffer sufficient wear to require replacement during the lay/plough operation. By determining the rate of wear in advance, remedial replacement of the plough share could be planned into the operation. To obtain a measure of this effect, a plough share was fitted to the fluke of the detrenching grapnel.

Operation and Results

The operation of route clearance and plough assessment was undertaken by the Dutch cable ship *D.G. Bast* with a BTI representative on board to monitor the performance of the grapnel and record all useful data. As for the survey, position control was maintained throughout by using HiFix 6. This afforded the accuracy and repeatability necessary for this work.

From the results obtained and the clearance work undertaken, it was determined that the route was ploughable.

Some elements of the route indicated the presence of high-strength material. However, ride-out did not occur, suggesting that full engagement of the plough would be possible along the whole route. The wear-down rate of the plough share was measured by weight and found to be 1%, indicating that replacement of the plough share would not be necessary.

As the survey results were obtained, the BTI project team assessed the cable protection requirements and passed the information to the system manufacturer, STC plc.

SUMMARY

This article has described the objectives, constraints and results obtained in selecting a route which would be suitable for ploughing for the UK–Belgium No. 5 cable.

There is a world of difference between land surveying, using a stable theodolite and visible fixed marks, and the rolling, heaving platform that a marine surveyor has to use. Allowing for the fact that marine surveying equipment is not as precise or infallible as might be desired, the route selected was considered to be the best available having regard to all the known physical conditions and artificial hazards.

Biography

Dick Whittington, who is a Master Mariner, joined the Post Office cable ship service in 1971 as a Third Officer, having spent the previous 12 years in the British Merchant Navy. He has served in all of BTI's cable ships in various ranks and has been involved in all aspects of planning, installing and maintaining submarine plant. He is currently Marine Planning Manager for submarine systems in BTI's Marine Services.

UK–Belgium No. 5

Part 2—Technical and Installation Aspects

R. D. CHANNON†

UDC 621.315.28 : 621.391.63

UK–Belgium No. 5, the world's first repeatered international submarine cable system to use optical fibres as the transmission medium was installed recently. The first of these two articles reviewed the marine aspects of the route selection[1]*. This second article reviews some of the characteristics of the system together with an outline of some of the planning and installation activities.*

INTRODUCTION

The world's first international repeatered optical-fibre submarine cable system has been installed between the UK (Broadstairs) and Belgium (Ostend). This 115 km long system, known as the *UK–Belgium No. 5*, supplied by STC plc, provides a capacity of six bothway 140 Mbit/s digital line sections. The ownership is shared between British Telecom (BT) on the one side and the Belgian RTT, Deutsche Bundespost and the Netherlands PTT on the other. This article gives a description of the system together with an outline of the planning activities, particularly those relating to the choice of route and on the testing, installation and performance of the system.

THE REQUIREMENTS

In the late-1970s, after a successful trial of a multimode optical-fibre system in the UK, planning commenced within British Telecom International (BTI) to introduce single-mode optical-fibre cable systems into the submarine cable network[2]. The first route selected was that between the UK and Belgium, one of the highest density traffic routes in the world. Although additional capacity on this route was not foreseen before 1987, the prospective Co-owners of the system recognised that an early implementation of the system would be of benefit because the period between the installation of the system and the expected traffic need could be utilised to carry out extensive tests and trials of digital network services, and to develop maintenance procedures.

THE ROUTE

Once it was agreed that a system would be installed between the UK and Belgium, the prospective terminal stations in which the cable system might be terminated were short-listed. The choice of terminal station was based upon consideration of easy access to a suitable landing point and to the national trunk network for connection to international exchanges. The terminal stations finally chosen were Broadstairs and Ostend, both of which are existing terminal stations for submarine cable systems.

The choice of landing points was based upon the suitability of the seaward approaches, diversity from other cables and the length of the land section. The landing points selected resulted in land sections of 1·7 km and 2·9 km at Broadstairs and Ostend, respectively.

Once the landing points had been chosen, the next step was to decide upon the marine route between them. Desk surveys were made to identify a possible route avoiding potential hazards such as mineral extraction areas, known fishing areas, existing cables, anchorage areas etc. The route also had to be suitable for burial. When a potential route had been identified from the desk study, a physical route survey was carried out in November 1982.

A hydrographic and geophysical survey was carried out by using echo sounding and side-scan sonar equipment to obtain detailed information of the sea bed. This information was supplemented by taking, at selected sites, samples from the sea bed to allow detailed analysis of its structure[1].

Whilst this survey information was being evaluated, the International Maritime Organisation proposed various changes to the shipping lanes, designated anchorage areas and pilot pick-up points off the Belgian coast adjacent to the proposed route. As a consequence, it was decided that the risks associated with ships anchoring close to the proposed cable route were unacceptable and that an alternative route should be found. An alternative, albeit more demanding, route was selected and a second route survey carried out. Fig. 1 shows the initial route passing close to the anchorage area, and the final route following closely the line of the old UK–Belgium No. 1 cable, which has recently been taken out of service.

It can be seen that the alternative route passes through a zone allocated for mineral (sand and gravel) extraction. Existing legislation automatically excludes licences being granted for mineral extraction where communication cables are laid. Although the route was chosen to minimise the area prohibited for mineral extraction due to the presence of cables, the final route (which for maintenance purposes keeps a reasonable separation between cables), together with the UK–Belgium No. 4 and Meridian cables, effectively closes the lower half of the zone for mineral extraction purposes. This choice of route was made after consultation with the Belgian mining authorities, and this part of the zone may now be re-defined so that the southern boundary takes a line to the north of the UK–Belgium No. 5 cable.

When all the surveyed data had been analysed, the actual route to be followed was finalised. The next decision was the choice of cable type and armouring. The basic cable type chosen was one of 45 mm (1·75 inch) diameter with a single layer of high-tensile steel armour wires over the polyethylene insulation. In areas where it was not practicable to plough-bury the cable, or where the sea bed conditions were such that the cable could not be guaranteed to remain buried at all times of the year, an additional layer of armour wire (rock armour) was applied over the first layer of armour

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† Satellite and Lines Executive, British Telecom International

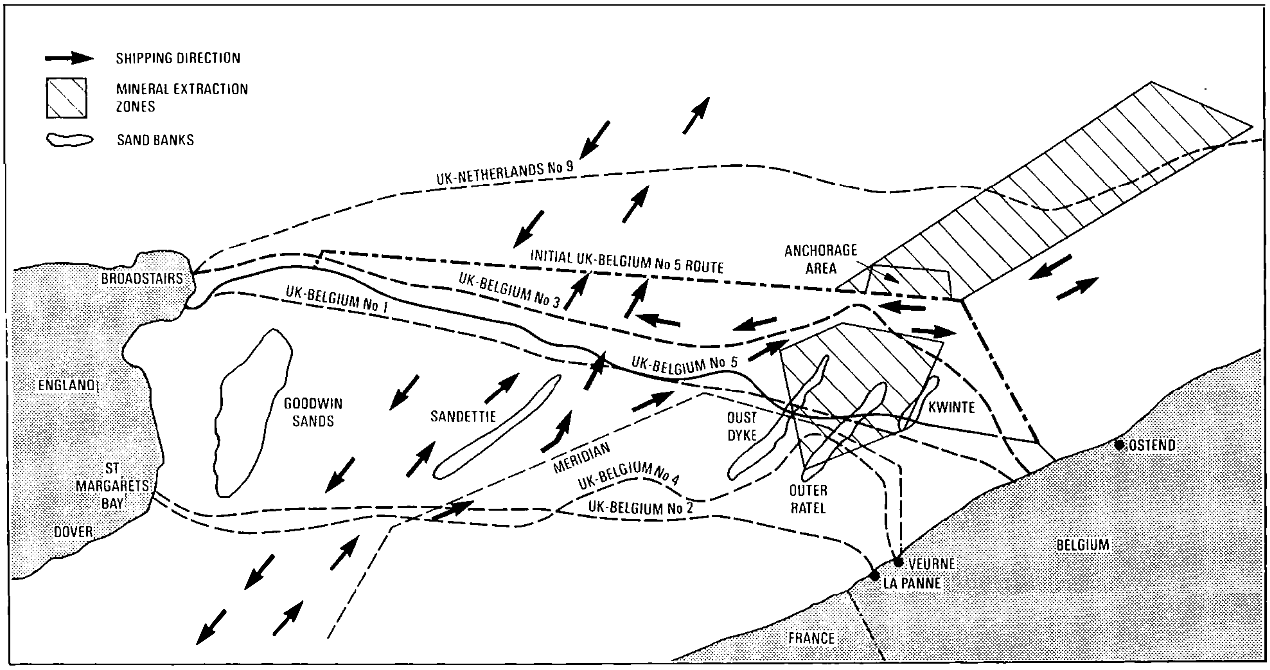

Fig. 1—UK–Belgium No. 5 cable route

wires. A straight-line diagram of the system showing the lengths of the various types of armoured cable is given in Fig. 2

As the proposed route passed through French territorial waters, permission had to be sought from the French authorities to lay, bury and subsequently to carry out any repairs to the cable. This permission was readily obtained enabling all details concerning the route planning to be finalised. All that remained was to clear the route of any old out-of-use cables to prevent them from fouling the plough during installation and to reduce the likelihood of their interfering with any subsequent repair operation.

SYSTEM CHARACTERISTICS

The system provides a traffic capacity of six bothway 140 Mbit/s digital line sections, over three pairs of optical fibres, each operating at 280 Mbit/s giving a total system capacity of 11 520 × 64 kbit/s circuits.

Wavelength The system operates at a wavelength of 1·31 μm over single-mode fibres with a nominal zero dispersion at this wavelength.

Input and Output Devices The optical transmitter used is a semiconductor laser which nominally launches a mean power of −1·9 dBm into the fibre. The optical receiver is a PINFET receiver with a typical sensitivity of −34 dBm.

Line Code The derived information bit rate is obtained by multiplexing two CCITT† 139·264 Mbit/s streams to a 283·776 Mbit/s signal. Before transmission to line, it is coded so that the design requirements of the submerged regenerators are simplified. The 7B8B line code used is a bounded code; that is, the number of consecutive like digits is limited. For this code, 7 bit data words are mapped to 8 bit words transmitted to line. Another property of the line code is that the digital sum variation is constrained to 6 which provides significant timing content in the data stream, thus greatly simplifying the clock recovery and re-timing circuit of the regenerator. The low frequency content of the line signal is limited allowing AC coupling to be used. The line rate of the encoded signal is 324·315 Mbaud/s.

CABLE DESIGN CHARACTERISTICS

The design objective for the cable requires that it must provide a very high reliability to ensure the stability and integrity of the fibres for a system design life of 25 years. The general design requirements for cable are that the fibres should be protected from excessive strain during

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† CCITT—International Telegraph and Telephone Consultative Committee

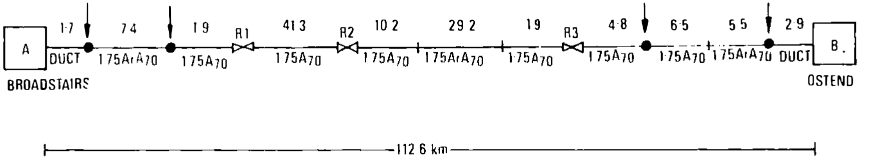


Fig. 2—Straight-line diagram of the system

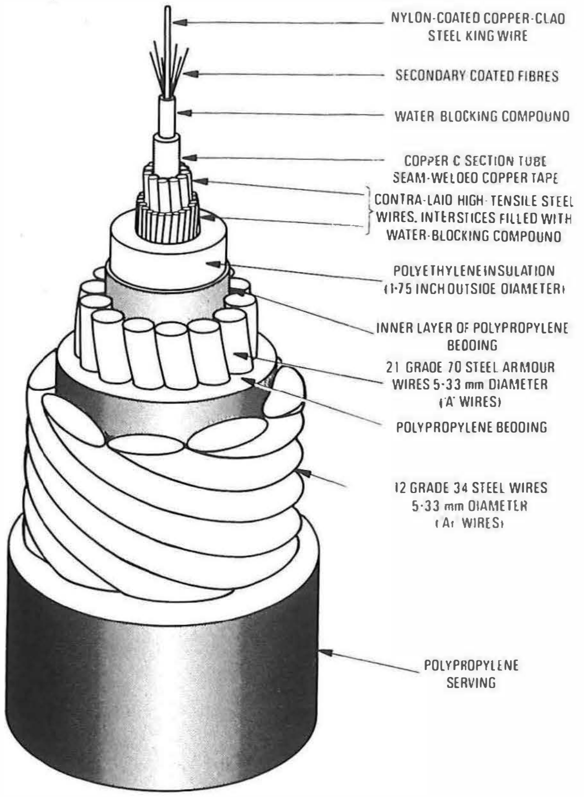


Fig. 3—Rock armoured cable type 1·75ArA$_{70}$

manufacture, laying and recovery, the pressure of the ocean and from water ingress. An analysis of the design requirements of cable is the subject of another article in this *Journal*[3].

The double armoured (1·75Ar A$_{70}$) cable to be supplied for this system is illustrated in Fig. 3. At the centre of the cable is an eight-filament package which comprises six fibres and two fillers which are laid around a central copper-coated steel king wire. This package is surrounded by a composite copper tube with the interstices between the copper tube and the fibres filled with a high-viscosity water-blocking compound. The thick-walled composite copper tube is made in two processes. Firstly the fibre package is inserted into a C-shaped section of copper into which the water blocking compound is injected, then the C section is closed and drawn into a round tube. Secondly, a copper tape is formed around this tube and is longitudinally seam welded and drawn down to form a hermetic tube which provides protection against hydrostatic pressure and a hydrogen barrier for any hydrogen generated or evolved externally to the copper tube[4]; the copper tube and the materials inside it are selected for their low hydrogen content. The effect of hydrogen on the attenuation of fibre is reported in other articles[5].

Strength is provided by two contra-laid layers of high-tensile-strength steel wires. The interstices between the layers of steel wires are also filled with a water blocking compound which limit axial water penetration in the event of cable damage. The composite copper and steel conductor provides the required low-resistance path for supplying power to the repeaters. A medium-density polyethylene layer is extruded over the steel wires to provide insulation of the power-feed conductor. The thickness of the insulation increases the overall diameter to 22 mm for land cable and to 45 mm for sea cable, the increased thickness of the latter contributes to the impact resistance of the cable.

To provide protection from external sources, one or more layers of steel wires surround the polyethylene insulation. When a cable is damaged, it is usually subjected to high tensile forces which, if any resulting elongation is transmitted to the fibres, will result in high residual strain, which in turn could lead to subsequent failure of the fibres because of static fatigue. To provide protection against excessive residual strain and the external impacts, a medium-tensile steel is used for the longitudinal armour wires. In areas where the cable is particularly vulnerable to trawl fishing, a second layer of armour wires is provided, but the lay length is very much shorter and provides very much improved resistance to impacts such as can be expected from beam trawls. The two types of sea cable, 1·75A$_{70}$ and 1·75Ar A$_{70}$ have virtually identical load versus elongation characteristics as the second layer of armour in the latter cable does not contribute significantly to its strength. Fig. 4 shows the load versus elongation characteristic of the sea cable which can withstand loads of up to 700 kN. The residual strain on the fibres once the load has been removed will be less than 0·1% which the fibres can withstand for the design life without failure due to static fatigue.

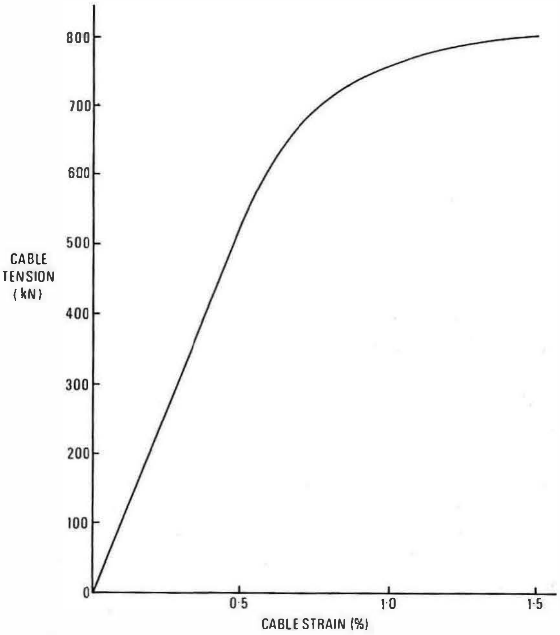


Fig. 4—Load versus elongation characteristic

The land cable, which is installed in duct, incorporates a longitudinal copper tape over the insulation which provides a safety earth in the cable and a return path for fault location purposes. A high density polyethylene sheath is extruded over the copper tape to bring the overall diameter to 31 mm

REPEATER DESIGN AND CHARACTERISTICS

The repeaters for submarine cable systems are designed having regard to performance and reliability to ensure operation over their design life of 25 years without adjustment. The specified failure rate of individual systems is usually expressed as *not more than three ship repairs over its life time* and this requirement applies to UK–Belgium No. 5.

Reliability influences every aspect of regenerator design and manufacture. In addition to the reliability objectives, the object of repeater design is to take maximum advantage of the power budget and, hence, to minimise the number of repeaters in a system whilst providing sufficient margins to satisfy the system design requirements.

Transmission Path

A block diagram of the transmission path of the regenerator is shown in Fig. 5. The receiver, a GaInAs PIN photodiode, is followed by a GaAs low-noise field-effect transistor (FET) and further amplification. The receiver is an integrating type of receiver and the circuit design, voltage rails and 7B8B line code characteristics, particularly the digital sum variation (DSV), result in a minimum sensitivity of −34 dBm and a dynamic range of 20 dB. After conversion of the optical signal to an electrical signal and subsequent amplification by a low-gain low-noise amplifier, the signal is regenerated.

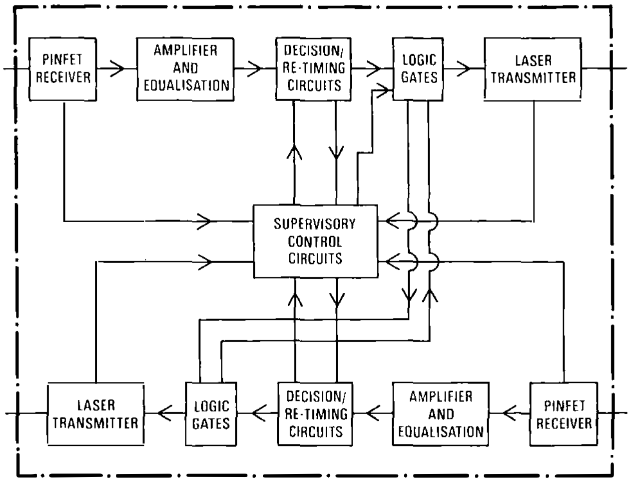


Fig. 5—Block diagram of a regenerator pair

Regeneration is accomplished by further amplification of the signal and by re-shaping and re-timing it in a decision circuit. The retiming is achieved by deriving a clock signal from the data stream by using a surface acoustic wave (SAW) band-pass filter with a centre frequency corresponding to 324·315 MHz and using it to drive a D-type bistable. The output from the regenerator is fed into the optical transmitter, where the binary signal is used to modulate the laser diode, which is a GaInAsP inverted rib waveguide (IRW) structure laser. The light output versus drive current of a typical laser is shown in Fig. 6, together with a modulation signal. The laser is biased to the knee of the light-versus-current characteristic to minimise turn-on delay. The amplitude of the data (modulation) signal determines the peak output power level. In order to maintain the amplitude of the modulated optical signal and the mean power within close tolerances over the life of the system, two control loops are required. They are provided within the transmitter control circuitry and are necessary for the following reasons:

(*a*) to maintain the laser biased to the knee of the laser characteristic (threshold current): as lasers age and/or temperature changes, the value of the threshold current changes (increases with time and temperature);

(*b*) to maintain the mean optical power output: as well as the bias current changing with time and/or temperature, some lasers exhibit a change (decrease) in slope of the current versus light output characteristic which would, unless compensated for, result in a reduction in modulation depth and mean output power.

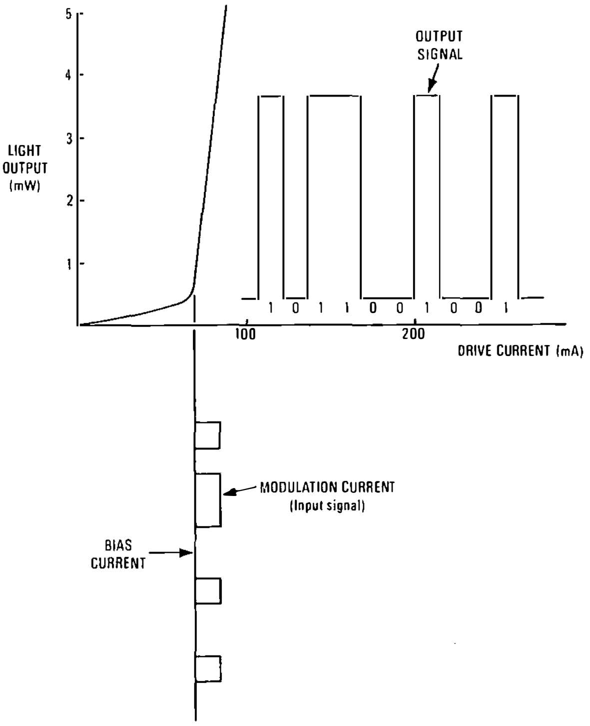


Fig. 6—Laser characteristic

Feedback loops are thus used to control the value of threshold current and the amplitude of the modulation signal to maintain the required output over the life of the system. A PIN photodiode incorporated in the laser package is used to monitor the light from the rear facet of the laser and thus to provide the control signal for the feedback loops. Within the laser package, the rear-facet monitor diode is mounted at an oblique angle to the laser chip on its heat sink to avoid reflection problems, since a second Fabry-Perot cavity could lead to spectral broadening and instability of the optical output signal. The mean output power from the laser fibre tail is typically −1·9 dBm. The optical output signal is coupled into a lensed fibre, which is metallised to allow it to be soldered in position on a pedestal (the thermal expansion of the pedestal is matched to the laser heat sink) and to be accurately aligned to the laser facet before the pedestal is welded in position. The whole laser package is hermetically sealed, the soldered metallised fibre providing a hemetic seal on the fibre entry into the package.

As the power supplied to repeaters is a constant current, an additional control circuit is provided to maintain constant the current drawn by each repeater over the life of the system. This maintains the current of the transmitter control circuit constant although the design allows the current drawn by the laser to vary by around 200 mA over its life.

Supervisory

In addition to transmission path circuit functions, supervisory circuitry is provided. The requirements of the supervisory system are to locate:

(*a*) with the minimum of ambiguity a failed repeater; and

(*b*) a repeater giving a high error rate.

These requirements are met by the provision of the following facilities in each repeater:

(*a*) measurement of the bias current of the laser;

(*b*) electrical loop-back of the transmission path of a pair of fibres in both directions simultaneously; and

(*c*) measurement of the received light level.

To activate these supervisory functions, each regenerator is addressed by a command signal. A response signal is returned to the terminal equipment as appropriate.

Telemetry commands from the terminal station to the repeaters are sent by means of a tone, frequency modulated on to the clock signal. Each regenerator pair has a unique address frequency in the band 18–28 kHz. In each regenerator, a frequency demodulator recovers the tone in the clock extraction circuit. The received level of the tone, determined by the frequency deviation applied at the terminal, is used to differentiate between the different supervisory functions.

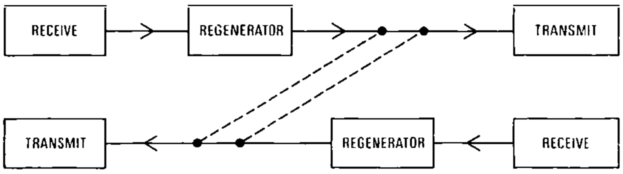
Laser Bias Current

By sending from the A-terminal the address tone of a particular regenerator pair at 13 kHz deviation, a signal corresponding to the bias current of the laser in the A→B direction of transmission is signalled back to the A terminal as phase modulation of the returned clock, the magnitude of phase modulation being proportional to the laser bias current. The frequency of the returned phase modulation is identical to that of the address tone of the regenerator pair addressed. To address the laser bias facility of the B→A regenerator, the same address tone and frequency deviation is applied from the B-terminal. A deviation of 13 kHz of the clock frequency does not cause any degradation in the system performance and hence this supervisory facility can be used with the system in-service.

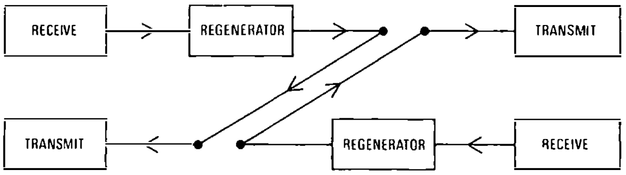
Electrical Loop-back of the Transmission Path

Fig. 7 shows the transmission path looped and, in particular, the relative location of the loop-back switches within the regenerator circuitry. The switches are constructed from logic gates by using the same family of integrated circuits as are used for the transmission path functions.

Operation of the loop-back switches for a particular regenerator pair is achieved as for the laser bias measurement, but with a frequency deviation of 25 kHz. This loop-back condition is referred to as *soft loop-back* because, by transmission of special data signals, it is possible to cause loop-back to be removed even though this level of frequency deviation is maintained. This property is outlined further in the description of the received light level facility.



(*a*) Normal configuration



Note: Transmission path looped back in each direction simultaneously

(*b*) Loop-back gates operated

Fig. 7—Electrical loop-back path

By increasing the frequency deviation to 44 kHz, a loop-back condition, referred to as *hard loop-back*, is initiated and cannot be overriden except by the command signal being removed. This loop-back condition is used when error monitoring from the terminal station around a looped regenerator pair is carried out.

When a fault is being located, either loop-back condition can be used; the looping of successive regenerators from either or both terminal stations is used to locate the faulty repeater or repeater section.

Received Light Level Measurement

The received light level at a regenerator can be measured by first looping-back (soft loop) the particular regenerator, as described above, and then by transmitting a special data pattern from the terminal station that passes through the receiver whose receive light level is to be measured. The special data pattern is formed of repetitive, selected 32 bit words which are injected in the terminal equipment into the transmitter (that is, at a rate of 324·315 Mbit/s). The special property of these data patterns is that each different 32 bit pattern generates different amplitude frequency sidebands. When analysed in the frequency domain, the dominant frequency component is 10·1348 MHz (324·315 Mbit/s ÷ 32 bit), henceforward referred to as 10 MHz. The 10 MHz component is filtered off in the receiver and its amplitude is compared to a reference voltage within the regenerator. By changing the repetitive 32 bit pattern, the 10 MHz content can be increased until its amplitude exceeds the reference voltage, at which point the loop-back command is overridden. By finding the pattern that just causes loop-back to be overidden, the received optical light level can be computed.

As the regenerator whose received light level is to be measured must first be looped-back, it is an out-of-service supervisory measurement.

Reliability

The system is designed to meet the reliability requirement of no more than three repairs to the submerged plant, caused by a component failure, over the 25 year life of the system. This requirement is achieved firstly by careful choice of components, in particular, during their manufacture, then carrying out vigorous qualification tests on each component and complete regenerators, carrying out life tests on components to enable their reliability to be ascertained and finally by screening components for use in the system[6].

The semiconductor component selected for the regeneration electronics is an integrated circuit manufactured by British Telecom Research Laboratories (BTRL)[7]. Because of the quantity required for each regenerator to provide the desired transmission path and supervisory functions, a severe reliability requirement is imposed upon the integrated circuits. Uncommitted logic array (ULA) integrated circuits based upon the ECL40 silicon bipolar technology of the Type 40 transistor[8, 9] were chosen. The Type 40 transistors are of the same family as those used in the STC NG 45 MHz analogue coaxial submarine cable system. To achieve the desired regenerator circuit functions, the final metallisation layer, which provides the connection between the various components on the integrated circuit, is different for each integrated-circuit design. This allows a single basic design of integrated circuit to be used to provide all the different circuit functions. Eleven different ULA designs are used to implement all the regeneration and supervisory functions.

In addition to the integrated circuit, other components, particularly those being used for the first time in submerged regenerators, for example, the IRW laser, the PINFET receiver and the SAW filter, were subjected to rigorous testing to ascertain whether they met the requirements of the system.

Power Feeding

Power for the submerged regenerators is supplied from the terminal stations over the power conductor in the cable via an earth return as shown in Fig. 8. Regenerator pairs are connected in parallel, deriving a stabilised voltage of −6·5 V across a Zener diode from the 1·55 A constant current supply. Other regenerator pairs are connected in series as shown in Fig. 9 and surge protection circuitry is provided over the repeater as a whole.

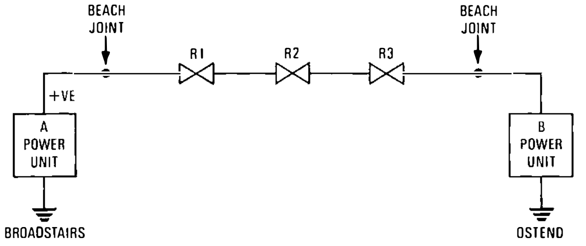


Fig. 8—System power-feeding arrangement

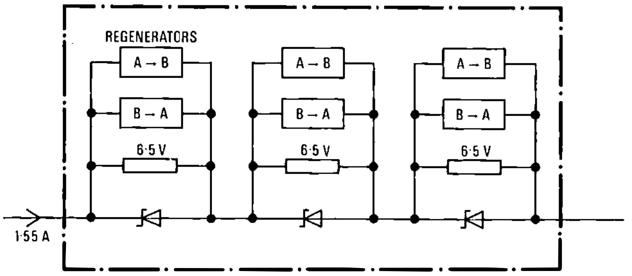


Fig. 9—Repeater power-feeding arrangement

Repeater Housing

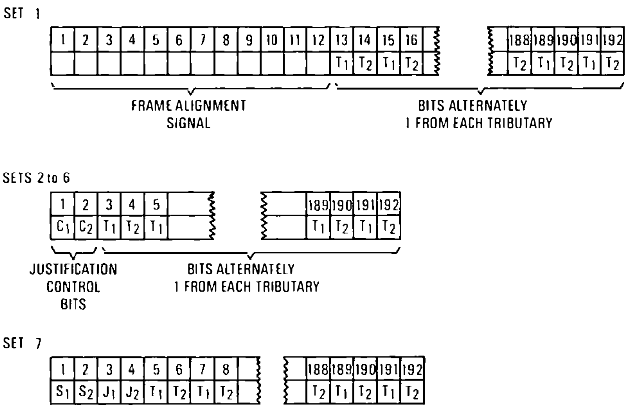
The repeater housing is very similar to that used for analogue coaxial cable submarine repeaters — a 275 mm diameter high-tensile steel casing with demountable bulkheads, which provide enhanced protection against sea-bottom pressures. An epoxy/coal tar/glass-fibre reinforced coating is applied to the external surface of the housing for protection against corrosion. The repeater interfaces with the cable via a cable termination, which is a 'tapered grip' termination, to the inner steel wires of the cable and, in the case of armoured cable, to the armour wires. The fibres are fusion spliced to the fibre tails of the electro-optic devices, which pass through water-tight feed through glands into a sealed splice pressure chamber[10].

TERMINAL EQUIPMENT

The transmission equipment for this system[11] provides the interface between the inland transmission network and the sea cable. Essentially, the equipment multiplexes two asynchronous 139·264 Mbit/s signals into a suitable format for transmission to line.

Transmission Equipment

The transmit equipment accepts two 140 Mbit/s coded mark inversion (CMI) encoded digital signals in accordance with CCITT Recommendation G.703. The two input ports each have duplicated inputs connected to a service protection network (SPN) switch enabling either the normal or standby input to be selected. After the SPN switch, the data is converted to a binary signal; the two data streams are then brought to a common rate by the insertion, as appropriate, of additional bits, scrambled, and frame alignment words (FAWs) inserted, before being bit interleaved to give a 283·776 Mbit/s signal. Fig. 10 shows the frame structure, which incorporates an FAW, two 211 kbit/s service channels and transmit control timing digits. The scrambler is an 11-stage set-reset scrambler.



1 Frame = 134 bits (7 sets of 192 bits each)
T_1, T_2 = Data bit from tributary 1 or 2 respectively
(Nominal bit rate = 139 264 kbit/s)
S_1, S_2 = Service digits for engineering speaker circuits etc.
J_1, J_2 = Justifiable digits (Maximum justifiable rate = 211 143 bit/s)
C_1, C_2 = Justification control bits
Nominal justified tributary rate = 141 888 kbit/s
Multiplex output rate = 283 776 kbit/s

Fig. 10—Frame structure for 2 × 139·264 Mbit/s multiplex

After being interleaved into a single digital stream, the signal is line coded (7B8B), which raises the data rate to 324·315 MBaud. After line coding, the signal passes through a buffer store which allows for the injection of supervisory signals when necessary. The output from this unit modulates the optical transmitter (IRW laser) to give the line signal. Fig. 11 shows a block diagram of the terminal transmission equipment.

The receive equipment detects and amplifies the incoming optical signal, and extracts the 324·315 MHz clock signal by using a SAW filter prior to regeneration. After regeneration, the signal is word aligned, decoded, the FAW detected, and the signal disinterleaved. These are all complementary

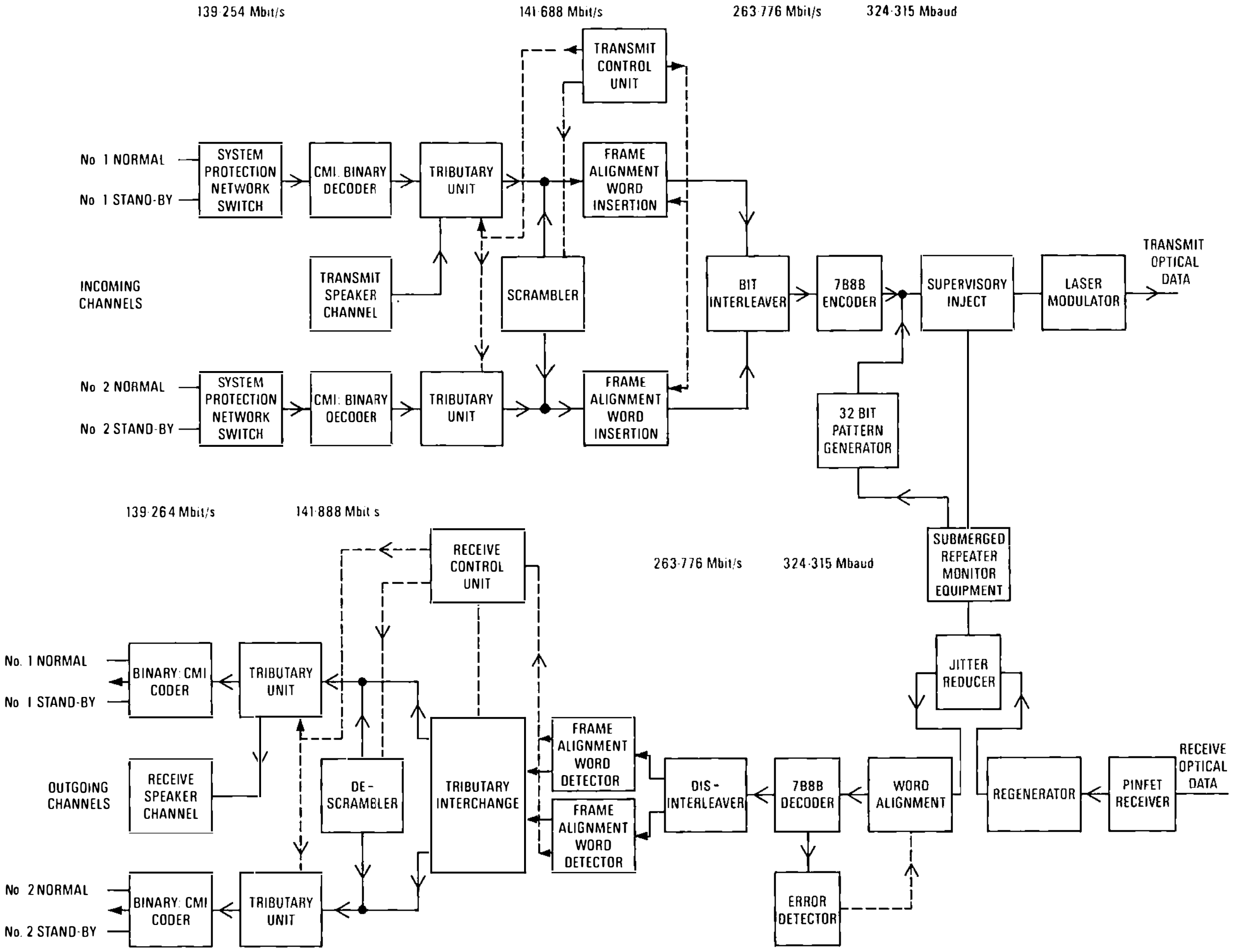


Fig. 11—Block diagram of terminal transmission equipment

processes of the transmit equipment. To ensure that the two streams are connected to their correct tributary, a means is provided to allow the two streams to be interchanged if the incorrect FAW is detected in the tributaries. The signals are descrambled and CMI encoded prior to connection to the duplicate traffic output ports. The transmission equipment for one pair of fibres is incorporated into one TEP 1E rack[12]. Four racks are provided at each terminal station: one for each of the three pairs of fibres, and the other as a maintenance spare.

SUPERVISORY EQUIPMENT

The submerged repeater monitoring equipment (SRME) is a minicomputer-based system which provides the telemetry commands to interrogate the repeater supervisory facilities and interprets and stores any returned signal. In addition, all terminal alarms are logged. Thus, a comprehensive record of system performance is maintained to allow the performance history of the system to be examined and to enable any potential failure to be analysed.

POWER-FEEDING EQUIPMENT

The power-feeding equipment (PFE) in each station incorporates duplicated 48 V 20 kHz converters which convert the station primary power supply to a 1·55 A constant current supply, with each converter having a voltage capability of 600 V. The normal mode of operation is for one unit from each terminal to supply nominally half the system voltage (double-end power feeding), with positive polarity from Broadstairs and negative polarity from Ostend. In the event of the failure of a power unit at either station, the stand-by power unit operating into a dummy load at the same terminal station normally takes the load. If the stand-by is faulty, the working power unit at the remote terminal station increases its voltage output to the total system voltage (250 V). This latter configuration is referred to as *single-end power feeding.*

SYSTEM PERFORMANCE REQUIREMENTS

Lifetime and Reliability

The performance requirements are that the system should have no more than three ship repairs due to component failure over the system life of 25 years. The reliability assurance is obtained by judicious choice of components and extensive tests as detailed earlier.

Transmission Performance

The system transmission performance is designed to not exceed over its life a long-term bit error ratio (BER) of $1 \cdot 12 \times 10^{-10}$ at the 140 Mbit/s interfaces. In addition, the bit error performance shall also be commensurate with the requirements of CCITT Recommendation G.821 which specifies the performance in terms of errored seconds, errored minutes and percentage of error-free seconds.

The other main transmission impairment is that of jitter, and the system is designed to meet the requirements of CCITT Recommendation G.703 for the jitter performance.

Loss Budget

The transmission performance requirements on BER are achieved by engineering each of the cable-repeater sections in the system to meet, under worst case conditions, a specified loss budget. For ease of explanation, the loss budget may be divided into a sensitivity and overload budget. A simplified sensitivity loss budget is shown in Table 1. It can be seen that this divides into two categories:

(*a*) limiting parameters at date of system installation, and

(*b*) allowances for ageing and repair margins which affect the initial sensitivity operating margins, this margin being expressed against a BER of 10^{-9}.

TABLE 1

Sensitivity Loss Budget

Launch power (minimum)	−2·8 dBm
Fibre loss (maximum)	20·2 dB
Receive level (minimum)	−23·0 dBm
Repair margin	3·0 dB
Operating margin	8·0 dB
Receiver sensitivity (minimum)	−34·0 dBm

In addition to the margin against sensitivity, a margin against overload, also expressed as the signal level that causes a 10^{-9} BER, is required. This margin, in addition to an operating margin, includes an allowance for ageing, which causes the system operating levels to increase. A simplified overload loss budget is shown in Table 2. For an average fibre loss of 0·47 dB/km at 1·31 μm, a nominal repeater spacing of 41·5 km can be achieved for a nominal fibre loss of 19·5dB.

TABLE 2

Overload Loss Budget

Launch power (maximum)	−1·1 dBm
Fibre loss (minimum)	18·9 dB
Receive level (maximum)	−20·0 dBm
Receiver overload (minimum)	−16·6 dBm
Overload margin	3·4 dB

For the 115 km UK–Belgium No. 5 route, three intermediate repeaters were required to meet the system performance and margin requirements. Additional losses in the end sections due to splices at approximately 0·5 km intervals, together with the provision of optical connectors in the terminal equipment do not allow the full section length to be realised in these sections (see Fig. 2).

TESTING PRIOR TO SYSTEM INSTALLATION

Comprehensive tests on terminal equipment, cable and repeaters were made during and upon completion of manufacture in the factory. These tests were supervised by BT personnel on behalf of the owners of the system.

The main sea sections of cable (the submerged cable sections except the sections laid in very shallow water), together with the repeaters, were temporarily assembled in the factory prior to laying and the system margins and performance measured. On completion of these tests, the system was dismantled prior to loading onto *CS Alert* for the main lay.

INSTALLATION

The system installation took place in four operations, firstly the land cable sections, then the shore-end cable sections, the terminal equipment and finally the main sea section.

Land Cable

The UK land cable was installed in January 1985 by BT Canterbury Area staff, tested by BTI staff and jointed by BTRL staff. This was followed by the installation of the Belgian land section which was jointed by BTRL staff as subcontractors to STC.

On completion of the installation of the land sections, the fibre pairs were looped back at the beach manhole to enable monitoring of the land sections.

Shore-End Cable Sections

The shallow water off the UK and Belgian coasts required a ship with a shallow draft to lay these sections of cable. The cable ship, *Directeur Generale Bast*, from the Netherlands PTT was used for this task. Because the *CS D.G. Bast* has a relatively small cable capacity, each shore-end was loaded and laid as sequential operations in September 1985.

Fig. 12—*CS D.G. Bast* laying shore end at Broadstairs

Fig. 12 shows the Broadstairs shore-end cable being installed. At the seaward end of each shore-end cable, the fibre pairs were looped back and the power-feed conductor connected to an earth electrode. The cable was jointed to their respective land cable sections in the beach manholes and tests were carried out from the terminal stations.

Terminal Equipment

The terminal equipment was installed into the respective terminal stations in March 1986. After the installation,

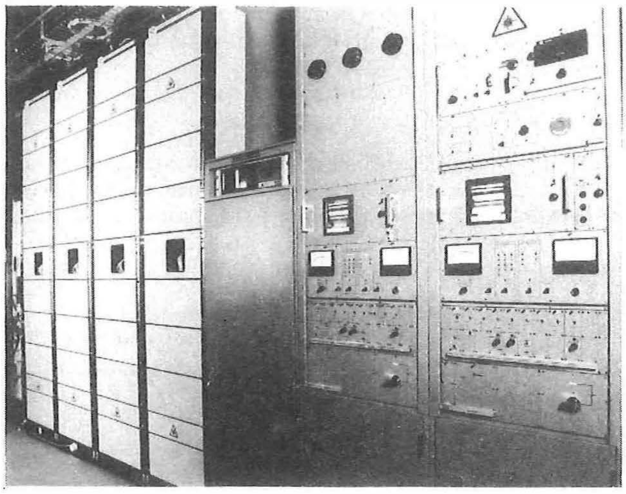


Fig. 13—Terminal equipment at Broadstairs

comprehensive tests were carried out which included a stability test for a period of seven days. Fig. 13 shows the terminal equipment installed at the Broadstairs terminal station.

Main Sea Section

The loading of the cable and repeaters for the main sea section on to the *CS Alert* commenced in April 1986. After the repeaters had been jointed into the cable and the system subsequently tested, the ship departed for the laying ground.

The route on which the cable was laid is one of the busiest shipping routes in the world. This, coupled with the strong cross currents that can be experienced in this area (particularly onerous when laying/ploughing at low speeds), necessitated a number of support vessels be chartered to assist in the laying operation; these included:

(*a*) two ocean going tugs to assist *CS Alert*, as required, to provide additional control during the ploughing operation,

(*b*) a Trinity House guard ship to warn other shipping in the vicinity of the laying ship, and

(*c*) the *CS D.G. Bast* to provide general assistance during the operation.

Upon arrival at the position of the end of the UK shore-end cable, the rope attached to the end of the cable was grappled and recovered. The cable was tested and jointed to the main sea section cable (initial splice). Upon completion of the initial splice, backscatter and insulation resistance tests were made on the cable prior to it being powered from the cable ship to an earth at Broadstairs. After transmission tests from the terminal station to special terminal equipment installed on the cable ship had been carried out and it had been ascertained that the system was operating as expected, laying/ploughing of the system commenced. During the installation, the system performance was continuously monitored up to a point where the end of the lay was being reached when the cable had to be de-powered and disconnected from the ship-board terminal equipment. The end of the Belgian shore end cable, which had previously been attached to a buoy, was recovered, tested and jointed to the end of the main sea section (final splice). Upon completion of the final splice, backscatter and insulation resistance tests were made from the Ostend terminal station prior to power being applied to the system from the terminal power-feed equipment.

After initial end-to-end transmission and supervisory measurements had been carried out and it had been confirmed that the system was operating as expected, *CS Alert* was released from the operation.

POST-LAY INSPECTION

Immediately after *CS Alert* had commenced the final splice, the Dutch survey ship *Volans* carried out a side-scan sonar/sea floor mapping operation of the whole route. On completion of the final splice, *CS Monarch* with Trencher[13] buried the final splice and the Belgian shore-end. Two locations along the route were then selected from the plough records and side-scan sonar survey results, and a survey/remedial burial was carried out. These post-lay operations indicated that the cable had been ploughed successfully in the very onerous environmental and operational conditions that exist in this area of the North Sea.

SYSTEM COMMISSIONING

Immediately following completion of the final splice, overall system commissioning commenced. These tests included tests to characterise the system and to demonstrate compliance with the system performance requirements. The culmination of the system commissioning was a 14 day stability test during which the transmission performance of each of the 139 Mbit/s tributaries was monitored. During this period, a total of three errors were recorded, two in one tributary and one in another of a different line system.

The system commissioning tests demonstrated that the system performance requirements were met by a considerable margin and, on the satisfactory completion of these tests, the system was initially accepted by the Co-owners. Final acceptance of the system will be carried out in two further stages subject to its continued satisfactory operation.

ADDITIONAL SYSTEM TESTS

After the initial acceptance of the system, additional tests over and above those called for in the system specification were carried out in order to characterise the transmission performance of the system. Tests were also carried out on a longer system created by looping at the input of the terminal transmitter and the output of the terminal regenerator. A system comprising 12 regenerator pairs or 24 one-way regenerators has been simulated equivalent to 600 km and 1200 km system lengths, respectively, for regenerator spacings anticipated for future systems of similar design.

One of the most important transmission parameters of long systems is that of jitter, and one of the measurements that has been made on the system is that of jitter accumulation after a number of regenerators. By using different looping configurations, a system with 4, 8, 12, 16, 20 and 24 regenerators was constructed. Fig. 14 shows the results

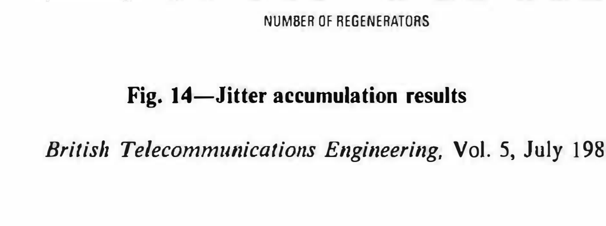


Fig. 14—Jitter accumulation results

of the RMS jitter accumulation measurements and confirms that the accumulation factor falls between the bounds of $n^{0.5}$ and $n^{0.25}$ as expected.

Another transmission parameter of interest will be that of obtaining data on error statistics; this is a long-term measurement and the accumulation of data has only just commenced.

CONCLUSION

The completion of the commissioning tests indicates that the UK–Belgium No. 5 submarine cable system has been successfully installed and is fully operational. The system will now be the subject of extensive tests and trials of all digital services. This system heralds the beginning of the era of optical-fibre digital submarine systems.

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Biography

Ray Channon is an Executive Engineer in the Submarine Cable and Microwave Division of BTI. He joined BT in 1965 as a Trainee Technician Apprentice and, after completing his training, worked on the maintenance of the trunk transmission network in the Guildford Telephone Area. On promotion to Assistant Executive Engineer in 1975, he joined the Submarine Systems Division, and was involved initially in the commissioning of analogue coaxial cable systems, and then carried out planning studies, prepared specifications and adjudicated tenders for submarine cable systems. In 1978, he joined a newly formed group to monitor and oversee the development of optical-fibre submarine cable systems. In 1981, he was promoted within the optical-fibre group to his present grade, where his main responsibility has been to provide technical support for the planning and provision of optical-fibre submarine cable systems.

TAT-8: An Overview

R. L. SMITH, C.ENG., M.I.E.R.E.,† and R. WHITTINGTON*

UDC 621.315.28 : 621.391.63

The eighth transatlantic telephone cable (TAT-8) will be the first system employing optical-fibre digital technology on this prestigious major route. British Telecom International has played a major role in planning the facility, in which it is a major investor. This article describes the planning processes, including the problems faced with the introduction of the new technology, and briefly describes the system and reports on the progress to date.

INTRODUCTION

In order to maintain close contact for planning transatlantic telecommunication facilities, potential European and American telecommunications investors set up a series of consultative meetings together with the USA Federal Communications Commission (FCC). This forum received the information in 1980 that it would be possible to lay an optical transatlantic cable, incorporating multiple landings, for use in 1988. Interested parties then started the detailed planning of such a facility—to become known as *TAT-8*. Twenty-nine different telecommunication entities in North America and in Europe notified their intention to participate in this cable. The American Telephone and Telegraph Company (AT&T) was the major investor with about 35%, followed by British Telecom (BT) with 15·5%; the cable was equally owned by entities on the eastern and western side of the Atlantic.

PRE-CONTRACT PLANNING ARRANGEMENTS

The first tangible step on the road to the implementation of the TAT-8 project was a meeting of potential owners of the system held in Bournemouth, UK, in September 1981. The early start was in recognition of the work to be done and to allow the owners to revert to the procurement of an analogue system in the event of the optical system being shown not to be viable. At this meeting, the owners decided that a number of specific problems relating to an optical system needed to be addressed, and set up specialist groups to study them.

The first problem was to identify the shape of the system to be provided; in other words, to study the traffic flow-predictions and assess which system configuration would most efficiently meet the owners' needs. This was especially necessary for an optical system because a system having multiple landing points by means of submerged branching units was now a possibility. The group set up to do this was called the *configuration working party* (CWP).

The second problem related to the technology and whether in fact a viable system meeting the owners' requirements could be made available in 1988. Associated with this task were studies into capacity, procurement and interconnection of the different digital hierarchies on either side of the Atlantic. A *technical working party* (TWP) was established to consider these problems.

A third group, called the *investment method working party* (IMWP), was set up to assess how the traditional methods of buying circuits in a cable needed to be modified in view of the digital optical-fibre technology proposed for TAT-8, particularly because of the prospect of multiple landings.

The outcome of all these groups resulted in the definition of TAT-8 as it is now being manufactured. The groups themselves worked closely together and made use of sub-groups to study particular aspects of the work. In addition to the other groups, a working party to draft the *construction and maintenance agreement* (C&MA WP) was formed to prepare for the formalisation of the agreement to proceed. Fig. 1 shows the structure of the committees formed to deal with the system planning stage.

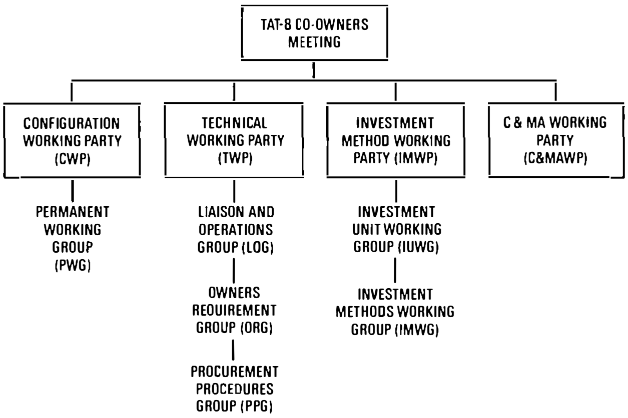

Fig. 1—TAT-8 co-owner arrangements for pre-contract planning

CONFIGURATION

The discussion on configuration, led by the Italian company Italcable, was given a wider scope than usual because of the possibility of using branching units on optical systems. This led to a large number of potential configurations with up to three landing points on either side of the ocean. By December 1982, this had been resolved to five main variants for the purposes of tendering (Fig. 2).

Eventually it was decided to proceed on the basis of configuration A (see Fig. 3) largely in recognition of the economics of adding longer spurs which would not carry high densities of traffic. It was, however, agreed that an Iberian branch could be added, if circumstances justified it later.

INVESTMENT METHOD AND UNIT OF INVESTMENT

The fundamental unit of capacity was identified as the bit per second in each direction. A unit of ownership designated as the minimum practicable unit of ownership and called the *minimum assignable unit of ownership* (MAUO) was agreed to be 73 684·656 bit/s. This comprises 64 kbit/s of usable data and the necessary additional bits to provide for multiplexing etc.; that is, equivalent to a voice channel.

For the simple configuration chosen, the owners agreed to use the overall average unit costing method whereby all intercontinental units would cost the same and the ownership would be equally split between eastward and westward co-

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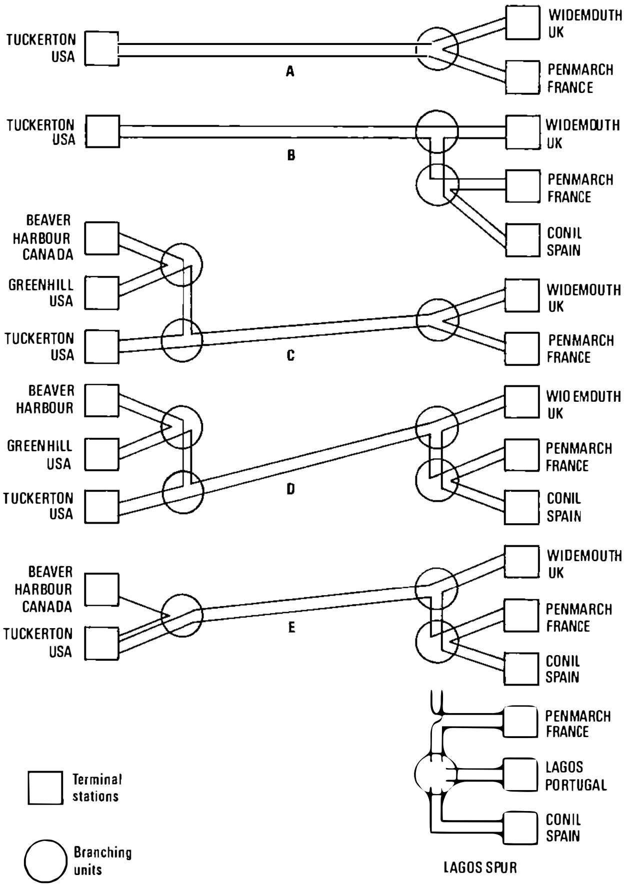

Fig. 2—TAT-8 possible engineering solutions

owners. Several other investment methods were identified, and may well be more appropriate to configurations having multiple landing points, spurs of uneven length and capacity demand. For example, a much longer spur may have to be financed by using an individual branching costing method where each branch is paid for by the carriers using it.

As well as the overall average unit costing method, which is based on the premise of 50/50 cost sharing between eastern and western partners and in which each owner pays the same amount for units of intercontinental traffic, several other methods were identified.

The individual branch costing method is useful for some owners who require longer branches or more lightly-loaded branches. They would finance that branch without cross-subsidisation from owners of a shorter branch.

Also, with the unitary arrangement of an optical-fibre cable system, it is possible to share ownership of pairs of fibre within the cable, each fibre pair taking its share of the common cable and repeater structure. This method was dubbed the *individual fibre pair costing method.*

Methods dealing with the incremental cost of adding fibre pairs to an already agreed configuration were also discussed, but these methods have the disadvantage of not being welcomed by parties owning the basic cable structure because they could be seen as cross-subsidising other users.

TECHNICAL AND PROCUREMENT ARRANGEMENTS

One of the early problems to be considered was the means of interconnecting the different digital hierarchies that had established themselves in the USA and Europe. The European system is based on the 2·048 Mbit/s 30-channel primary unit using A-law encoding, whereas the USA system is based on 1·544 Mbit/s 24-channel primary unit using μ-law encoding. After studies of the frame structure, signalling etc., a special hierarchy was agreed for use on TAT-8. It comprises intermediate levels at 2–45–140 Mbit/s in order to match the primary levels to the TAT-8 system interface of 140 Mbit/s. Access at 6·3 Mbit/s can also be arranged by bilateral agreement. This hierarchy has now been accepted by the CCITT†.

The TWP arranged for a request for quotation (RFQ) to be sent out to submarine cable system manufacturers in the Atlantic region in December 1982. Tenders were returned in May 1983.

The RFQ comprised a general specification which defined the user requirements for TAT-8. Compiling this document was particularly challenging because there were no previous systems to give a background for the specification, few CCITT criteria etc. Therefore, the owners had to develop their own standards for performance of the system. The RFQ also comprised route detail, proposed contractual conditions and other contractual details such as payment conditions, price schedules and programme details. Also, a section was written about the arrangements for final testing of the link

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† CCITT—International Telegraph and Telephone Consultative Committee

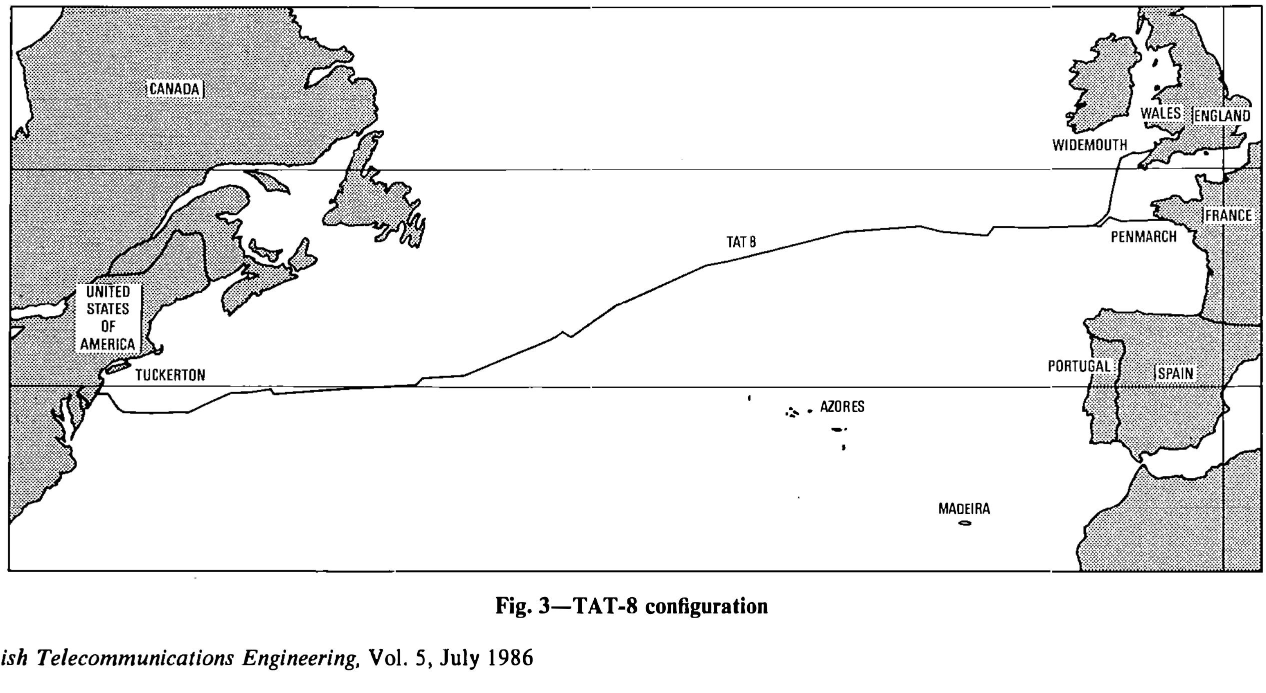

Fig. 3—TAT-8 configuration

leading to acceptance by the owners and the liquidated damages to be applied if the system did not comply with performance or delivery requirements. Warranty requirements were also detailed, the owners requesting prices for warranty periods of 2, 5 and 10 years.

Tenders were received from AT&T-Communications (AT&T-C), Submarcom (a French company combining the resources of Les Cables de Lyon and CIT-Alcatel), and STC plc of the UK. The tenders were backed up by a presentation of their facilities and resources to representatives of the co-owners in June/July 1983.

After a detailed assessment of the tenders and discussion of various adjudication methods, recognition of the effect of varying exchange rates, the closeness of the bids, and national interests, it was decided to proceed with a system design integrating the systems of the three tenderers.

This alternative solution was for each of the tenderers to supply part of the system. The individual system designs had to be modified to accommodate this arrangement and AT&T were charged to be the lead supplier, responsible for co-ordinating integration activities with the other two suppliers.

The resulting system arrangement is shown in Fig. 4.

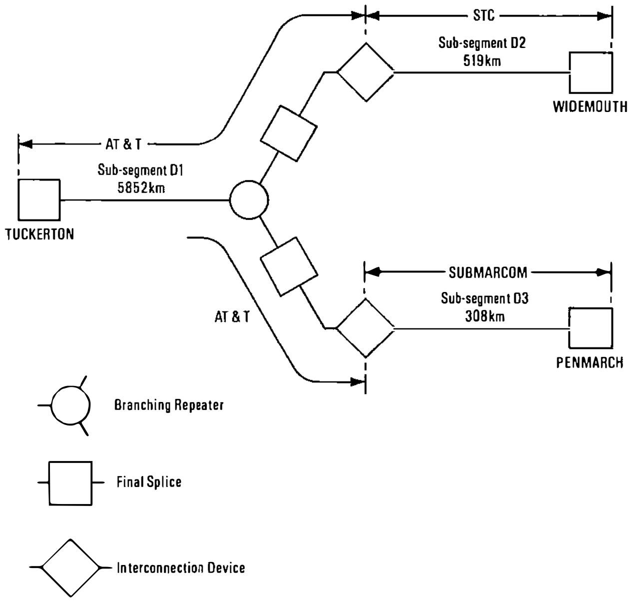

Fig. 4—TAT-8 system route

CONTRACT PLACING

The planning phase of the project came to an end in January 1984, when a construction and maintenance agreement was initialled by the potential owners. The decisions forming the basis for this agreement are summarised below:

(*a*) an optical system was feasible for service in 1988;

(*b*) the use of a branching unit was feasible, but for TAT-8 only a simple branch should be considered;

(*c*) the configuration was agreed;

(*d*) a solution to the digital hierarchy incompatibility was noted, at the time, in principle;

(*e*) financial parameters for ownership and investment were agreed; and

(*f*) an engineering solution based on the three tendered systems was agreed.

The next few months were taken up with discussions between suppliers to assess the means of arranging for actual compatibility of their product and deriving the specification for the interface conditions. Also, there was activity in finalisation of the contracts between the suppliers and the owners. These contracts were eventually signed on 12 July 1984. The contracts were actually placed between each supplier and the Co-signatories of TAT-8 on behalf of all the co-owners. The Co-signatories were AT&T-C, BT, and the French Administration des Postes, Télécommunications et Telediffusion (FPTT).

IMPLEMENTATION PHASE

To monitor and control the project during the implementation phase, the co-owners organised themselves on similar lines to previous transatlantic projects (see Fig. 5).

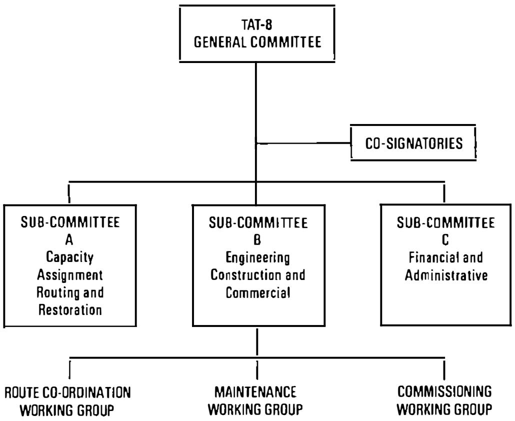

Fig. 5—Project control arrangements

The General Committee comprises senior managers from all the co-owners and meets when necessary, normally about once a year, to give overall direction to the project and sub-committees and to plan utilisation strategy.

The Co-signatories have a special role for interpretation of contractual details and, additionally, are directly responsible to the General Committee for integration matters.

Three sub-committees were set up:

Sub-Committee A to deal with the operational aspects of connecting a digital cable between the two continents,

Sub-Committee B to deal with the project management of the three contracts and the associated co-ordination, and

Sub-Committee C to monitor the cost of the project.

An important feature of the engineering sub-committee B is the identification of the methods that need to be developed to maintain the system. These include the means of fault localisation on the system as well as the equipment necessary to do this, and any special equipment needed to joint the optical-fibre cables, train the operatives etc. For this reason, a *maintenance working group* (MWG) has been established. Another sub-group of sub-committee B studies the survey requirements and difficulties of choosing a suitable place for laying the branching repeater. It has also been noted that topics relating to the commissioning and acceptance of the system will need to be studied by a *commissioning working group* (CWG).

The contracts were organised so that there were two major milestone reviews (31 March 1985 and 31 December 1985) at which the owners had the opportunity to review with the contractors the development progress and assess the build-up of reliability information.

ROUTE SELECTION AND MARINE CONSIDERATIONS

As mentioned in the previous paragraph, one of the key decision areas relates to the choice of a secure route, especially the location of the branching point.

With regard to the shallow water areas of the route, an

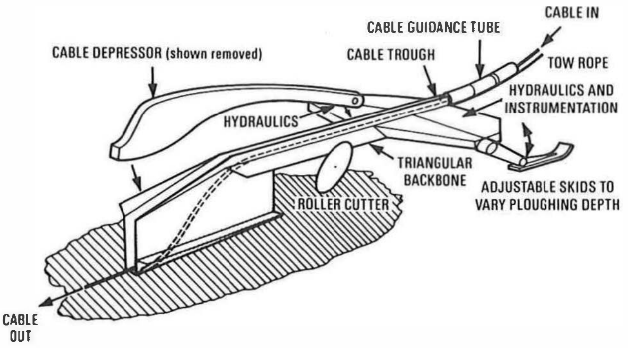

Fig. 6—British Telecom submarine cable plough

early decision was taken to protect the cable by burying it in the sea bed. BTI has, through British Telecom Research Laboratories (BTRL), developed a cable plough (Fig. 6) which has a number of potential advantages over the American and French equivalents. Various trials and early operational work have been undertaken to prove the new plough. In order to extend this method of protection, it is being further developed to bury cable at depths of 950 m. The BTI plough will operate from the *CS Alert* and will bury most of the STC-made part of the system from Widemouth, in Devon, to a point 950 m deep some 500 km from the shore.

The route from the UK to the branching unit will be surveyed by BTI using the latest navigational aids and sea-bed survey methods. Typically, side-scan sonar techniques and the use of the detrenching grapnel over the route enable sea-bed conditions to be ascertained. From this data, together with information concerning fishing and other sea-bed activities, the best practicable route for the cable is selected.

The originally passive branching unit, which is to be supplied by AT&T-C, now incorporates regenerators and is termed a *branching repeater*. As well as handling power-feed switching, it will contain some fibre flexibility points.

The original location for this branching repeater was chosen from a study of charts of the likely areas. A suitable location was found on a small plateau at about 2000 m depth around which the Continental Shelf quickly slopes down to the Abyssal Plain (Fig. 7). A special survey, however, found that suitable access into shallow water from the plateau was narrower than first thought. The French and UK spurs would therefore have to be closer together with the consequent potentially increased risk of a single hazard causing damage to both. The owners are presently studying whether adequate protection can be given or whether an alternative route will have to be found.

SYSTEM DESCRIPTION

The TAT-8 system comprises two pairs of fibres: one pair is routed from Tuckerton, USA, to Penmarch, France, and the second from Tuckerton to Widemouth, UK. The two pairs separate at a branching repeater off the European Continental Shelf and, to keep symmetry within the cable and facilitate restoration, a fibre pair is provided between the UK and France. The branching repeater provides for switching of the fibres between the different locations for operational security reasons. The branching repeater also ensures that power to the submerged plant can be fed from either the UK or France by means of a switch activated by the initiation of power. It is necessary to feed power from

Fig. 7—Three-dimensional route map showing location of branching repeater

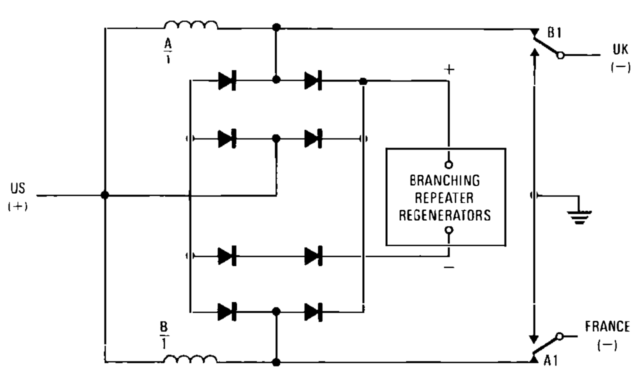

Fig. 8—Power-feed arrangements at branching repeater

both ends of the system for the transatlantic link. The spur not feeding to the USA feeds to an earth at the branching repeater (Fig. 8).

Each fibre pair carries two bothway 139·264 Mbit/s digital line sections. These two nominal 140 Mbit/s line sections are combined together into a 280 Mbit/s signal which, together with engineering facilities, is transmitted to line at a baud rate of 295·6 Mbaud.

The 140 Mbit/s line sections are made up by multiplexing 3 × 45 Mbit/s tributaries, each obtained from 21 × 2 Mbit/s blocks, which provides a total system capacity of 3780 × 64 kbit/s digital bearers per fibre pair. Digital circuit multiplication systems[1] can be used to provide the equivalent of 40 000 speech circuits. Although the multiplex equipment below 140 Mbit/s is not included in TAT-8, it can be seen from this paragraph how the problem of digital compatibility has been solved by a compromise between standards from Europe and North America.

The interface between the inland networks and the TAT-8 terminals is at 140 Mbit/s, and the performance of each 140 Mbit/s line system is specified according to CCITT Recommendation G.703.

A common line current and line code were the fundamental agreements forming the basis of the integrated system. The line current is 1·6 A and the line code is 24B1P.

As can be seen from Fig. 4, AT&T is to provide the system from Tuckerton up to and including the branching repeater. The Submarcom and STC systems connect from a position just east of the branching repeater to France and the UK, respectively.

The systems of each manufacturer differ in many respects; basically, however, the systems provide optical-fibre communications systems over single-mode fibre at a wavelength of about 1·3 μm.

Cable design is again different for the three suppliers. Each design provides a home for the fibres along the neutral axis of the cable. Features such as tensile strength, protection from pressure, hydrogen and water ingress are provided by other concentric layers of the cable. Hydrogen, an ever present hazard in submarine cables, was a major worry during the design of the optical cable when the effect of hydrogen on optical fibre became known[2].

A layer of insulation is provided to protect the high-voltage power-feeding current on the central package. In shallow water, the cable is further protected by a layer(s) of armour wires of varying size according to the type of protection required.

The three manufacturers have a different philosophy in their approach to achieving the specified system reliability. The owners' requirement was for the whole system to have a design life of 25 years and that only three ship repairs due to equipment failure were allowed.

To support their claim to meet this requirement, each of the manufacturers has set up a comprehensive life-testing programme of all the components used in the system. Also, the suppliers have used redundancy arrangements to a greater or lesser extent. The AT&T-C design, for example, has a separate pair of fibres completely equipped with regenerators which can be switched in at each repeater in order to by-pass any breakdown. All suppliers have provided cold stand-by laser transmitters which can be switched on and into circuit in the event of the failure of a working laser. Submarcom have used a measure of redundancy in the receiver and regenerator circuits and STC have duplicated the laser transmitters only.

The supervisory arrangements allow the system operators to monitor the performance of the undersea plant and take corrective action to restore service or locate the fault for maintenance action; this is described elsewhere in this issue of the *Journal*[3].

Typical facilities provided are an indication of the error rate at each regenerator, incoming light level and condition of the laser signal to line. In addition, the send and receive fibres can be looped at each repeater to enable absolute performance checks to take place from the terminal.

Operation of the terminal facilities to access repeater performance is controlled by computers at each terminal. Each digital line system terminal is duplicated with change-over points between set 1 and set 2 to provide minimum protection to service and meet the CCITT requirements for outage.

CURRENT STATUS

The current status of the project is that the main effort on the part of the suppliers has been to complete the development leading to a series of test programmes to demonstrate the compatibility of the three suppliers' designs. It is gratifying to be able to report that the first six phases of this work have been successfully completed. This means that repeater prototype models from AT&T, STC and Submarcom have successfully worked together and the terminal optical and multiplex equipment has also been shown to be compatible. The three manufacturers have also delivered all equipment for final testing in the USA.

Presently, the programme is on schedule for each sub-segment to be laid and accepted by 15 May 1988 in order that overall testing can be completed by 30 June 1988 for the system to be taken into service.

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Biographies

Roger Smith joined the Post Office, as it then was, as a Youth-in-Training in the Cambridge Telephone Area in 1958. He moved to Main Lines Development Department in 1965 and is currently Projects Manager for Submarine Systems and International Repeater Stations in BTI's Satellite and Lines Executive.

Dick Whittington, who is a Master Mariner joined the Post Office cable ships in 1971 as Third Officer, having spent the previous 12 years in the British Merchant Navy. He has served in all BTI cable ships in various ranks and has been involved in all aspects of planning, installing and maintaining submarine plant. He is currently Marine Planning Manager for submarine systems in BTI's Marine Services.

TAT-8 Supervisory Subsystem

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UDC 621.315.28 : 621.391.63

The in-service supervisory subsystem developed for the UK leg (segment D2) of TAT-8 allows for the measurement at each regenerator of received light level, laser health and line errors, and for redundant laser switching and loop-back. It uses outbound signalling by means of line parity bit violations, and shorebound signalling by angle modulation of the data rate. In each regenerator, the subsystem is realised on six metallisations of two uncommitted bipolar arrays of the ECL 40 family, one of which was developed specially for this work.

INTRODUCTION

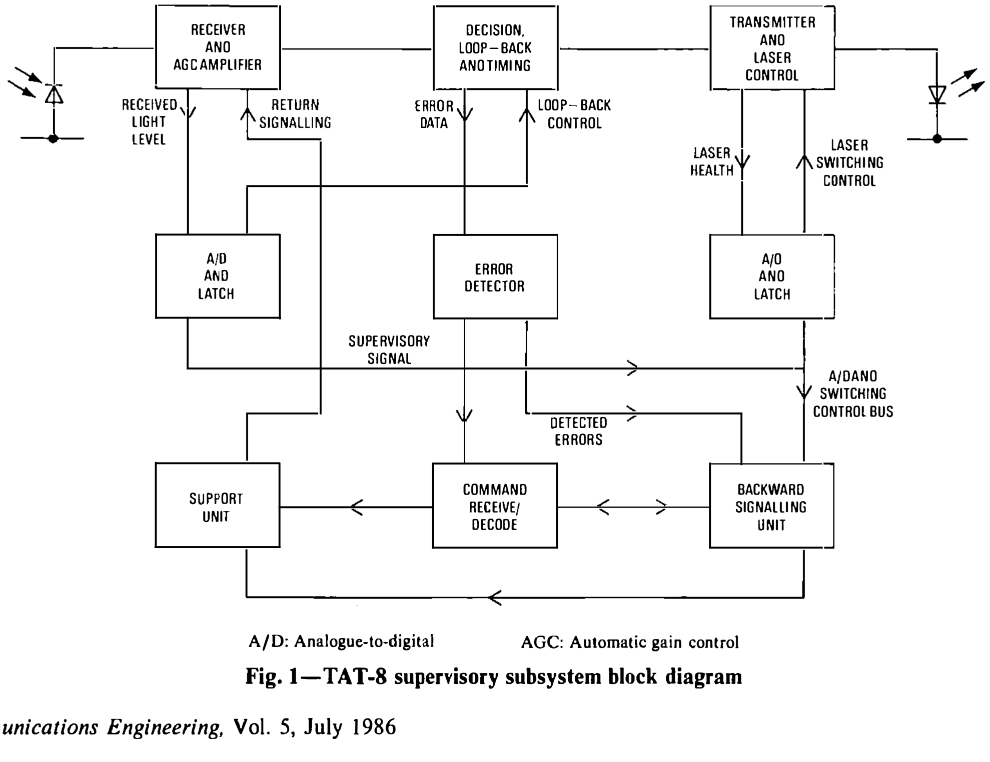
The award of the TAT-8 contracts in 1984 to each of three tenderers precipitated a great deal of redevelopment work for each of them, but more particularly for the British and French manufacturers, since they had submitted proposals for systems which differed most in their essential parameters from the system eventually standardised upon. For STC plc, the change was quite fundamental, because it had proposed a 7B8B line code, which allowed surface-acoustic wave (SAW) filters of relatively low Q factor (around 150) to be used. This in turn allowed the use of the frequency modulation (FM) supervisory system, already accepted for the UK–Belgium No. 5 system, on a long-haul system. With the change of line code to the new standard (24B1P), all this had to be replaced[1].

The 24B1P line code is, in effect, unbounded, and requires the use of SAWs having a Q factor of greater than 400. A Q of 800, the same as that used by AT&T, was adopted to avoid possible alignment jitter problems at the system interface. The narrow bandwidth of these SAWs precluded the use of the FM supervisory system (which requires a pair of modulating frequencies per repeater) on a system segment which, although it was to contain only 13 or 14 repeaters, STC wished to develop as a general long-haul system (NL2). The new supervisory developed for NL2 uses digital repeater addressing. In the outbound direction, violation of the line-code parity bits is used for signalling, and, in the shorebound direction, angle modulation of the data is used. (Although this is similar to the FM supervisory system, only one frequency is used, whereas many frequencies would have to be used to address many repeaters.) Regular parity-bit violation allows a tone to be detected at each repeater by means of a small addition to the error detector, and this tone can be keyed on and off to provide a signalling channel. The same tone, once present in the repeater, can be used to angle-modulate the shorebound data.

This article deals exclusively with the supervisory subsystem on TAT-8 segment D2, to be supplied by STC.

SYSTEM OUTLINE

A block diagram of the repeater supervisory subsystem is shown in Fig. 1. A digital word, encoded at the shore terminal and containing repeater address and command information, is fed to a shift register for decoding. Functions not requiring data transmission to the shore are executed immediately. An 8-stage counter on the backward signalling unit is used for error counting and (in conjunction with ramp generators on the analogue-to-digital and latch chips) for analogue measurements. The contents of this counter



A/D: Analogue-to-digital AGC: Automatic gain control

Fig. 1—TAT-8 supervisory subsystem block diagram

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are encoded on the support unit chip and the output of this is used to modulate the shorebound data stream.

Each repeater has four regenerators. Each regenerator has a unique address, and can be accessed from any of the four fibres serving the repeater. Data can be returned to either shore as required by the operator. The frequency of parity-bit violation has been chosen to make mutual interference between the USA and UK supervisories impossible.

FACILITIES

The supervisory subsystem provides several features, some available with the system in-service and some requiring it to be taken out of service. The facilities available are summarised in Table 1.

TABLE 1
Supervisory Facilities

In-Service	Main path error count Received light level Laser health Laser switching
Out-of-Service	Main path loop-back

A discussion of the general requirements and use of these facilities is covered in a companion article[2].

Analogue Measurements

Two of the required facilities involve measurement of an analogue parameter.

Received Light Level Indication

An indication of received light level allows the performance of the receiver to be monitored and assists in the location of a break in the fibre or a poor joint in the system. An accurate measure of joint loss implies a repeatable accuracy of the order of 0·05 dB, which is difficult to achieve in the environment of a repeater. However, a less precise indication (of the order of 0·5 to 1 dB) still offers sufficient information to aid in the identification of faulty fibres or failing receivers.

The precision of the measurement as implemented varies with received light level, being of the order of 0·1 dB at rated receiver sensitivity, degrading to 1 dB at 10 dB higher power input, and falling off more rapidly beyond this.

Laser Health Indication

A measure of the health of the active laser in a regenerator is essential where the use of redundant lasers is being considered. A minimum requirement would be a flag to indicate that the laser had aged so much that the circuitry providing the mean bias current was reaching the limit of its capability. Additional information indicating how rapidly this limit has been approached can allow more precise estimation of the remaining useful life of the laser. For lasers which are not suffering abnormal degradation, this could extend by several years the period between a predetermined limit being reached and the laser being switched out of use. A measure of laser health which returns more information than just a flag is thus very desirable.

The implementation of this measurement gives a measure of the amount of drive current available to the laser, to a precision of about 2% of the maximum drive current. Measurements can be recorded and plotted against time to reveal the trends in the laser characteristic. The proximity of the measurement to the zero reference, together with the levelling-off of the trend in the measurement as the current limit is reached, should allow a good estimate of the optimum time to switch in the redundant laser.

Error Counting

The system is designed to have an overall error rate of 10^{-9} or better at the end of its 25-year life. Design margins are such that the start-of-life error rate of each repeater will be many decades lower than this when measured in the factory. Practical systems produce errors in bursts from a variety of causes[3], and the sources of these errors must be traceable while the system is in service. The system therefore provides for the counting of errors at each repeater over an interval to be determined by the system operator. The use of an even-parity block line code allows errors to be detected by the even mark parity process, and to be totalised in an 8-stage (256-bit) counter.

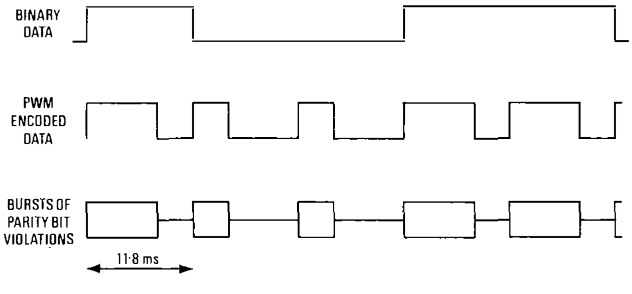
Loop-Back, Redundant Laser Switching and Return Signalling

Electrical loop-back and redundant laser switching are implemented in a straightforward manner. Information relating to laser health and error counts can be returned to the originating terminal, or sent onward to the far terminal, at the choice of the operator.

TECHNIQUES

Outbound Telemetry

Details are given below of how a message bit error, however caused, produces a signal at the output of the error detector in the repeater. This lends itself to a convenient signalling technique in which parity bits of the 24B1P line code are deliberately violated. Regular violations every third frame produce a 17·6 kHz tone at the output of the bistable circuit which can be filtered out by using a band-pass filter (see Fig. 2). This tone is used as a subcarrier to form a pulse-width modulation (PWM) channel; it is also used to disable the error counter. Fig. 3 shows how supervisory messages are encoded. The choice of the PWM format allows anisoch-



PWM: Pulse-width modulation

Fig. 3—Encoding of outbound supervisory data

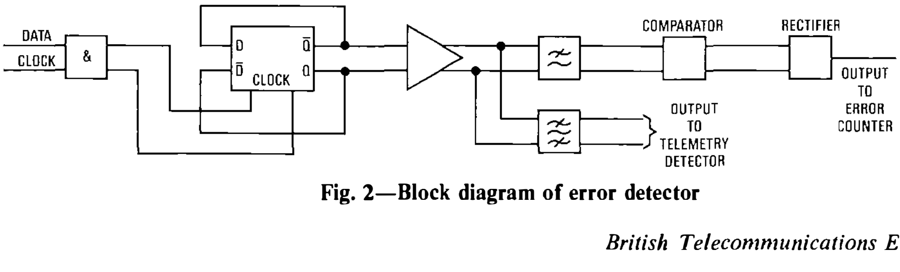


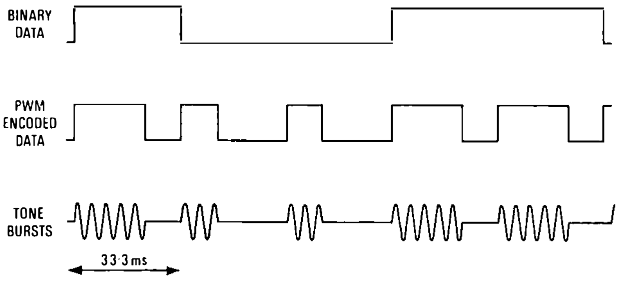
Fig. 2—Block diagram of error detector

ronous signalling and simple timing recovery to be used. A monostable triggered from each positive-going edge causes sampling of the PWM waveform 5·9 ms later, and, on the basis of this sample, the message bit is decoded as ZERO or ONE. The band-pass filter is selected to give a margin against a 10^{-9} error rate on the channel, and this is sufficient to allow for loss of performance due to ageing in the detector circuitry. This determines the signalling rate of 85 baud.

Supervisory commands are encoded in a 15 bit word, which is transmitted twice to allow verification. This word size allows up to 1024 regenerators to be addressed with the full command repertoire. If verification is unsuccessful, command processing is aborted. This is done to ensure that supervisory signalling is uncorrupted in the presence of line errors.

Shorebound Telemetry

Telemetry to the shore is by angle modulation of the shorebound data. The basis of this method was developed for the UK–Belgium No. 5 system[4]. A tone is used to vary the significant instants of the data with time, so that the tone can be demodulated from the extracted clock at the receive terminal. The 17·6 kHz tone is derived from the outbound signalling, and is used as a subcarrier to carry 30 baud PWM in the same way (see Fig. 4). This channel carries information about the laser health, the received light level, or the line error count in the form of an 8 bit word. The noise source on this channel is the system jitter, and, because it is difficult to guarantee an error rate as low as 10^{-9} at 30 baud, the 8 bit word is transmitted as many times as necessary to allow verification.



PWM: Pulse-width modulation

Fig. 4—Encoding of shorebound supervisory data

Analogue Measurements

The two analogue measurements—received light level and laser health—use common circuitry in the main supervisory controller, and a common design of interface circuitry; however, the parameters which are measured are derived in different ways and have different characteristics.

Received Light Level Indication

The received light level is monitored indirectly by measuring the tail current flowing in the automatic gain control (AGC) stage of the data amplifier in the main transmission path. This results in a monitor voltage which varies roughly proportionally to the gain of the AGC stage and hence inversely to the received optical signal level. Although the characteristic is roughly linear with respect to absolute power level, the quantisation steps, when mapped into decibel variation in optical power, result in a precision which varies significantly with optical power input. Fortunately, the finest precision occurs at lowest power levels, where it is most likely to be necessary. At the rated sensitivity of the receiver, the precision of the measurement is of the order of 0·1 dB.

Laser Health Monitor

The laser health is monitored by measuring the mean bias current flowing in the laser. This is accomplished indirectly by determining the residual current available from the mean-power control circuitry of the laser. This circuit operates differentially, in order to maintain the overall current consumption of the laser control circuitry at a constant level despite changes in laser characteristics. Thus, a voltage proportional to the remaining current is readily derived by inserting a small-value resistor in the collector connection of the balancing transistor.

Analogue-to-Digital Conversion

The voltages representing laser health and received light level are converted into a digital representation in an identical way.

The analogue-to-digital converter measures the input voltage by using a counter to assess the time taken for a voltage ramp to change between a reference voltage and the one of interest. If the rate at which the voltage ramp changes and the clock frequency of the counter are known, the count gives a measure of the difference between the two voltages.

In a remote repeater, the clock frequency and the ramp rate are affected by ageing, and temperature and supply-voltage variations. This problem is overcome by using a reference voltage, generated internally to the analogue-to-digital converter, to calibrate the measurement. By performing a measurement, firstly, on the reference voltage, and, secondly, on the parameter voltage, the ratio of the two resulting counts gives the ratio of the parameter voltage to the reference voltage. This procedure allows for large variations in counter clock frequency and ramp speed with only a small effect on the precision of the measurement.

A counter of eight bits is used, and this gives an attainable precision of ±0·4%. However, manufacturing and ageing tolerances in the analogue portions of the circuitry result in a true accuracy of five or six bits; that is, an achievable precision of ±1·5–3%.

Error Counting

Even Mark Parity Error Detection

Monitoring of the line errors at the repeaters relies on the even mark parity scheme[5,6], in which error detection consists of changing the state of a bistable every time there is a ONE (or MARK) in the data and monitoring its mean output voltage for changes. A block diagram of the error detector is shown in Fig. 2. The TAT-8 line code is 24B1P, in which a parity bit is added to each 24 message bits to give an even number of MARKS (ONES) in each 25 transmitted bits. With reference to Fig. 5, consider what happens to the output of the bistable circuit during transmission of a 25 bit word. The bistable changes state an even number of times and thus at the end of the word is in the same state as when it started. As there is an odd number of bits in the word, there

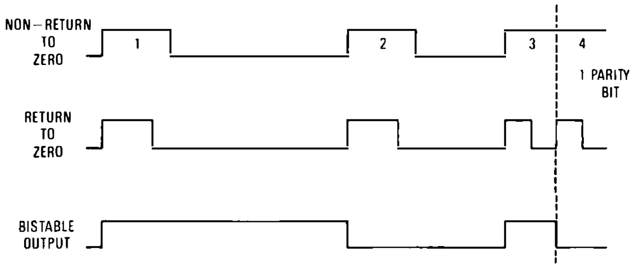


Fig. 5—Even mark parity code

is a small DC output offset. If odd mark parity is introduced, either by a single data bit in error or by deliberate parity-bit violation, the bistable output changes state an odd number of times and thus ends up in the opposite state to the state at the start of the word. The DC offset has now changed sign. If no further errors occur, this is the new stable state.

The change of DC offset is extracted by a low-pass filter and converted into a pulse by a threshold detector. The characteristics of the filter are important because they determine the highest and lowest measurable error rates.

Error-Rate Measurement—The Upper Limit

The system described above can detect isolated errors with 100% success. However, when the time between errors becomes comparable with the time constant of the filter, success becomes uncertain because the mean bistable output changes again before the filter output has crossed the threshold (see Fig. 6). The same occurs with any even-numbered burst of errors. Odd-numbered bursts are still detected successfully, however (see Fig. 7).

If errors occur randomly, as they would if caused by random noise in the repeater circuitry, then the maximum measurable error rate rises as the filter bandwidth is widened.

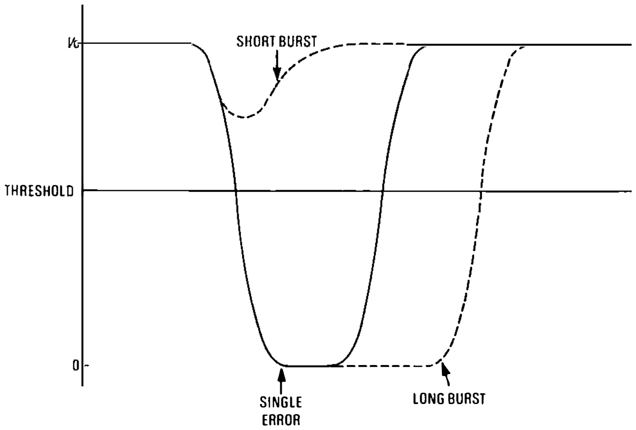


Fig. 6—Rectifier output

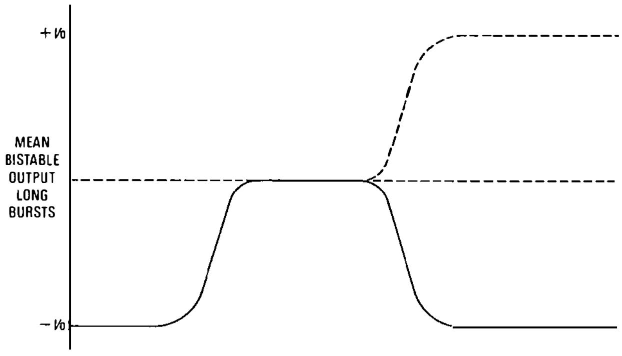


Fig. 7—Burst error detection

Error-Rate Measurement—The Lower Limit

The data input to the low-pass filter can be considered as a DC component with additive noise. The noise spectrum is continuous and essentially uniform within the band of the low-pass filter. The noise causes spurious triggering of the threshold detector even when there are no line errors. The spurious triggering rate depends on both the bandwidth and the order of the filter.

Long-Term Error-Rate Measurement Range

Selection of an appropriate bandwidth and order of low-pass filter has been made by calculation and confirmed by experiment. Table 2 shows the maximum measurable and background (spurious) error rates for two different types of simple filter (first and second order) of various bandwidths.

TABLE 2

Error Detector Performance
24B1P Code, 294·4 Mbaud

Filter Band-width (Hz)	First-Order Filter		Second-Order Filter	
	Spurious	Maximum	Spurious	Maximum
20	$<10^{-64}$	$1{\cdot}42\times10^{-8}$	$<10^{-64}$	$1{\cdot}30\times10^{-61}$
50	$<10^{-64}$	$7{\cdot}50\times10^{-15}$	$<10^{-64}$	$8{\cdot}30\times10^{-29}$
100	$<10^{-64}$	$2{\cdot}64\times10^{-9}$	$<10^{-64}$	$1{\cdot}00\times10^{-17}$
200	$<10^{-64}$	$1{\cdot}86\times10^{-6}$	$<10^{-64}$	$5{\cdot}30\times10^{-12}$
500	$<10^{-64}$	$1{\cdot}23\times10^{-4}$	$<10^{-64}$	$2{\cdot}30\times10^{-8}$
1 000	$5{\cdot}60\times10^{-38}$	$6{\cdot}00\times10^{-4}$	$<10^{-64}$	$5{\cdot}54\times10^{-7}$
2 000	$1{\cdot}50\times10^{-20}$	$1{\cdot}58\times10^{-3}$	$3{\cdot}60\times10^{-40}$	$3{\cdot}85\times10^{-6}$
5 000	$5{\cdot}70\times10^{-10}$	$3{\cdot}63\times10^{-3}$	$5{\cdot}00\times10^{-19}$	$2{\cdot}03\times10^{-5}$
10 000	$2{\cdot}30\times10^{-6}$	$5{\cdot}81\times10^{-3}$	$8{\cdot}10\times10^{-12}$	$5{\cdot}20\times10^{-5}$
20 000	$1{\cdot}74\times10^{-4}$	$8{\cdot}74\times10^{-3}$	$4{\cdot}66\times10^{-8}$	$1{\cdot}18\times10^{-4}$
50 000	$2{\cdot}99\times10^{-3}$	$1{\cdot}43\times10^{-2}$	$1{\cdot}38\times10^{-5}$	$3{\cdot}17\times10^{-4}$

These show that the first-order filter is preferable because it gives a larger measurable error-rate range when the maximum rate is set to around 10^{-5}.

REALISATION

Hardware

All the circuitry in the supervisory subsystem is implemented on chips using the ECL 40 process developed by British Telecom Research Laboratories. This approach was taken to allow compatibility with the technology used for the main-path integrated circuits (ICs), and to avoid the need for the lengthy and expensive qualification procedure required for a new process. As a result, the circuit configurations used are based on the standard emitter-coupled-logic structure using differential long-tailed pairs. Since this configuration is generally noted for high power consumption, and since many of the supervisory circuits did not need high-speed performance, most of the supervisory subsystem was designed with tail currents of 0·5 mA or less. Despite this, the overall power consumption of the supervisory subsystem is around 0·5 A with a 6 V supply.

The supervisory subsystem is implemented with a total of five IC designs, one of which (the analogue-to-digital converter and interface latch) is used twice. Of the five designs, two are implemented on 8-cell uncommitted arrays, identical to those used for the main-path circuitry, while the remaining three were developed by using an 80-cell array evolved from the 8-cell array specifically for implementing supervisory functions. As a rough indication of the level of complexity of each of the arrays, the smaller one comprises 128 transistors and could accommodate four master-slave flip-flops, while the larger comprises 1200 transistors and could accommodate 40 master-slave flip-flops.

The design was split functionally as follows:

Command Decode Unit (80-cell array) This performs the functions of command word reception and error detection, command decoding and unit address detection.

Backward Signalling Unit (80-cell array) This performs the functions required to acquire data for signalling back to the shore terminal. These include a counter for accumulating detected line errors and a shift register for converting the data to serial form. The counter also doubles as part of the analogue-to-digital converter.

Support Unit (80-cell array) This combines some of the functions associated with command reception and backward signalling. A counter to maintain a record of the number of supervisory command bits received is included, as are the timing circuitry and modulators required for backward signalling.

Analogue-to-Digital Converter and Latch (8-cell array) This chip incorporates the analogue functions associated with the analogue-to-digital conversion process (ramp generator, reference voltage generator, comparators). Also included is a latch and some interface circuitry to allow this chip to control the loop-back switch or the switching process between redundant lasers.

Error Detector and Interface (8-cell array) This implements the error-detector function and, in conjunction with a band-pass filter, extracts the supervisory PWM signal from the main path.

The last two functions were implemented on the 8-cell array mainly because they need predominantly analogue circuits and consequently have a large number of pin-outs relative to the chip area. Also, the 8-cell IC was already a qualified product with a very low worst-case failure rate established by extensive testing. The 80-cell array is a more recent design, and, although it is inherently as reliable as the 8-cell array, it has not yet completed its full life test programme. The functional design of the supervisory subsystem interposes 8-cell ICs between the main transmission path and the more complex supervisory circuitry on the 80-cell arrays. Thus a failure on one of these arrays would be extremely unlikely to affect the main transmission path. This fail-safe aspect of the design of the supervisory subsystem also allows the reliability level of the transmission system to be derived from the known failure rate of the 8-cell ICs.

Measured Error-Detector Performance

Fig. 8 shows the measured characteristic of the error detector using a first-order filter of an appropriate bandwidth. The corresponding theoretical background error rate of less than 10^{-20} clearly could not be measured in a reasonable time, and in any case its exact value is unimportant. The experiment does confirm that error rates down to 10^{-12} can be accurately measured.

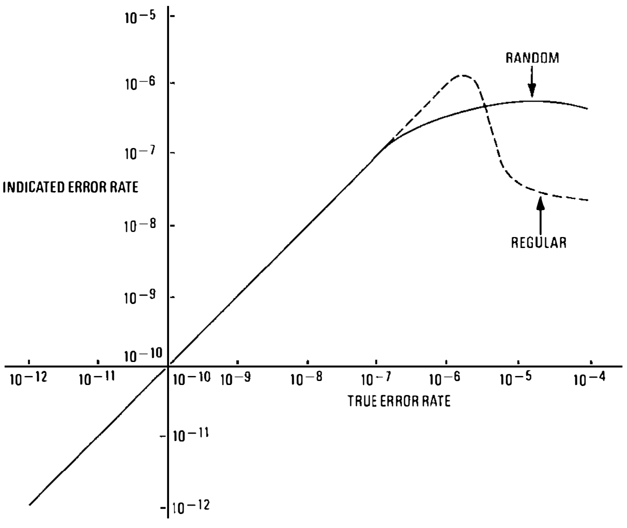


Fig. 8—Measured error-detector characteristic

CONCLUSION

The supervisory subsystem developed for the UK segment (D2) of TAT-8 and described in this article is likely to be usable, with only minimal modification, on many future-generation systems. Its use of digital addressing allows up to 1024 regenerators to be individually addressed. This is enough for a transatlantic system with two fibre pairs, and could be quadrupled with only minor changes to subsystem logic in the repeater. The outbound telemetry channel can be used in conjunction with any line code lending itself to even mark parity error detection (5B6B, 7B8B, 24B1P etc.). The shorebound telemetry can cope with SAW filter Q values of up to 800, a value which is suitable for unbounded line codes and therefore very unlikely to be exceeded.

Loop-back, redundant laser switching, and error counting facilities are provided at each repeater. Received light level can be measured to an accuracy of 0·1 dB and laser bias current can be monitored. The repeater subsystem is realised on uncommitted arrays of the high-reliability ECL 40 family.

ACKNOWLEDGMENT

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Biographies

Paul Dawson passed the Institution of Electrical Engineers part III examination in 1969, and obtained the M.Sc. degree in Electronics from the University of Southampton in 1972. Between spells of academic study, he spent periods with Pye-TMC and the Plessey Company. He joined the then Post Office Research Department in 1972 to work on speech-band data modems and digital transmission in the local network. After a period heading a group running Pathfinder, the first British public stored-programme control telephone exchange, he joined the Submarine Systems Research Division in 1981 to head a group primarily concerned with the development of optical-fibre submarine repeaters.

Alan Kitchen studied Electrical and Electronic Engineering at Manchester University and graduated with second-class honours in 1973. He joined the then Post Office Research Department in 1973 to work on picture compression techniques for visual telephone systems. In 1980, he transferred to the Submarine Systems Research Division to work on circuit design for optical-fibre submarine repeaters. Shortly afterwards, he spent a period at the University of Essex studying Telecommunications Systems, and received an M.Sc. in 1981. For the last two years, he has been involved with the design and implementation of the regenerator supervisory subsystem for TAT-8.

User Requirements and Provision of Digital Circuit Multiplication Systems for TAT-8

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UDC 621.315.28 : 621.391.63

This article discusses the user requirements for circuit multiplication systems to be used on the TAT-8 optical-fibre submarine cable system and describes the procurement procedure for the equipment.

This article is based on a paper presented at the Suboptic 86 Conference, Versailles, France, Feb. 1986.*

INTRODUCTION

Speech interpolation equipment was introduced into the international network in mid-1960 when time assignment speech interpolation (TASI) equipment was used on the transatlantic TAT 1 submarine cable system for the London–White Plains route. TASI was used to increase the circuit capacity of early TAT and CANTAT cable systems by exploiting the silent time which exists in every telephone conversation—they were the first circuit multiplication systems (CMS).

The early TASI-A and TASI-B systems were purely analogue equipment, which clipped the front end off the initial word or phrase in a sentence while the real-time detection of the incoming signal took place. Also, they used pulse-amplitude modulation (PAM) techniques to interpolate the speech.

Succeeding generations of CMS have become available since those early TASI days and digital speech interpolation (DSI) with integral delay is generally used virtually to eliminate the front-end clipping of speech. However, most route applications of CMS are analogue and require an internal or external digital/analogue interface between the DSI and the switching equipment or transmission medium. This analogue interface overcomes interworking and network interfacing difficulties which might apply when the CMS incorporates DSI designed to operate by using 1·5 Mbit/s μ-law or 2 Mbit/s A-law pulse-code modulation (PCM) principles and is the converse of the network in which the CMS terminal is located. The use of CMS on analogue transmission media between networks using different digital standards also avoids similar incompatibility problems.

CMS have always been used on a system basis because it is necessary to have complete compatibility for control-channel information and configuration between the two distant terminals. Since the network application for CMS has been small, the CCITT‡ and manufacturers have not devoted effort, with two exceptions, to establishing international standards which would enable terminals from different manufacturers to be compatible.

Table 1 lists the present range of CMS commercially available and their interfaces. Comments on Table 1 regarding CMS application in the international network further illustrate their limitations for use in an entirely digital international network where interworking between different digital standards would be required.

NETWORK PLANNING OBJECTIVES FOR THE TAT-8 DIGITAL CIRCUIT MULTIPLICATION SYSTEM

The *technical working party* (TWP), responsible for planning TAT-8 itself, established a *liaison and operations group* (LOG) so that the network implications of using TAT-8 could be studied.

The LOG studied three major aspects of TAT-8 usage:

(*a*) the digital hierarchy which should be used between North America and Europe;

(*b*) the advantages of using digital CMS (DCMS) and the transiting benefits of locating the DCMS at international gateways; and

(*c*) the technical requirements for the DCMS itself.

The first point, the 2–45–140 Mbit/s hierarchy adopted for TAT-8, has been discussed and recommended by the CCITT.

On the second point, it was decided that there would be definite transit cost advantages in locating the DCMS at international gateways or as close to them as possible. It was also decided that digital technology could offer greater advantages than DSI alone by combining low rate encoding (LRE) and DSI so that a DCMS should be able to achieve an overall 5:1 circuit multiplication in a network environment. This decision meant that DCMS would have to be operated with an entirely digital bearer side (Fig. 1). In some instances no digital capacity would exist over which to route the DCMS bearer to certain international gateways. The alternative would be to route trunkside circuits from those gateways to a DCMS located in the nearest or most convenient administration/company's digital network, hence the concept of the collecting-point DCMS was born.

The third point, the technical requirements for the DCMS is covered below.

The TAT-8 DCMS is required for the same fundamental reason as the early TASI and other CMS: namely, to increase the telephony circuit capacity of a transmission medium. But, additionally, it is required to have enhanced applications as a means of interfacing with either T1†† 1·5 Mbit/s μ-law or CEPT** 2 Mbit/s A-law transmission and switching equipment and, consequently, providing interworking between the two networks employing those different digital standards.

The DCMS is further intended to be a forward-looking equipment which will provide certain facilities for CCITT

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* COTTERILL, D. A. *et al* The user requirements and provision of digital circuit multiplication systems for TAT-8. Proc. Suboptic 86 Conf., Versailles, Feb. 1986, pp. 353–359.

‡ CCITT—International Telegraph and Telephone Consultative Committee

†† T1 is the independent standards committee sponsored by the Exchange Carriers Standards Association and is accredited by the American National Standards Institute

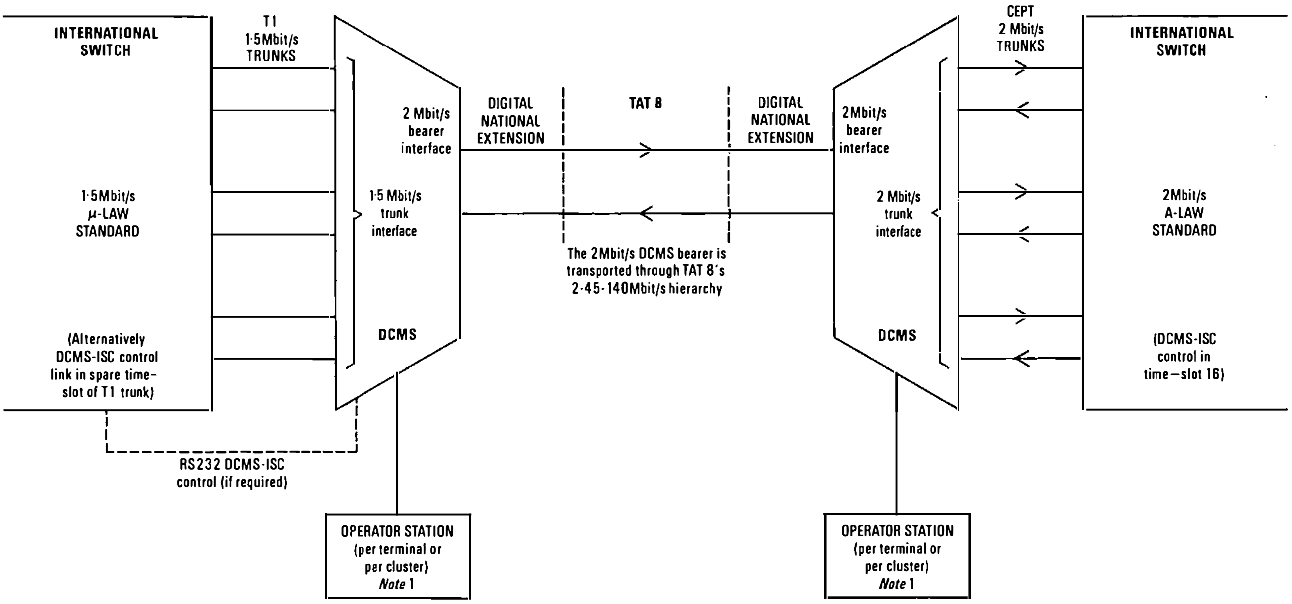
** CEPT—Conference of European Postal and Telecommunication Administrations

TABLE 1

Currently Available Circuit Multiplication Systems and Their Usual Application

System	Manufacturer	Size	Interface	Digital Standard	Application
CELTIC 2G	CIT-Alcatel	240/120	2 Mbit/s or analogue with PMUX	2 Mbit/s A-law	Public telephony routes. Usually over analogue transmission systems
CELTIC 2G/E (TASI-E compatible) *Note 1*	CIT-Alcatel	240/120	2 Mbit/s or analogue with PMUX	2 Mbit/s A-law	Public telephony routes over analogue transmission systems and with TASI-E as the distant terminal
COM 2	Republic *Note 2*	31/16 maximum	Analogue	μ-law	Primarily private circuit networks. It is compatible with CCITT No. 5 and R2 public telephony signalling
TASI-E	AT&T-Technology *Note 3*	240/120 maximum	1·5 Mbit/s or analogue with D4 PMUX	1·5 Mbit/s μ-law	Public telephony routes. Usually over analogue transmission systems
TLD or DTX	ECI Telecom	48/24 maximum module size	1·5 Mbit/s or analogue	1·5 Mbit/s μ-law	Public telephony or private circuit routes
DTX-30	ECI Telecom	60/30 maximum	2 Mbit/s or analogue	2 Mbit/s A-law	Public telephony or private circuit routes
TDMA/DSI	DCC(UK)Ltd, NEC Japan and Alcatel-Thomson, France	240/120	2 Mbit/s or analogue	A-law	Satellite routes. Burst-mode transmission from earth station terminal equipment

Notes: *1.* A CELTIC 2G/T1 is also available for use in the North American and other 1·5 Mbit/s μ-law digital networks
2. Formerly Comtech and originally Storage Technology Corporation
3. Formerly Western Electric



Note 1: Single terminals might use an optional on-equipment control panel instead of an operator station

Fig. 1—Typical system configuration

No. 7 signalling links, leased circuits and integrated services digital network (ISDN) requirements where clear-channel 64 kbit/s bit sequence independent transmission will be necessary.

Therefore, the term *digital* as applied to the DCMS does not refer so much to the internal operation of the equipment, which is entirely digital, as to the environment in which the equipment is intended to be used.

TAT-8 DCMS REQUIREMENTS

Overall Objectives

The LOG comprised members from various North American and European administrations/companies, all with slightly or considerably different requirements for a DCMS. Some required a very simple system which could be installed in any equipment room and used with the minimum of training for operations and maintenance personnel. Others required a more sophisticated terminal which would be remotely controlled from centralised network management centres and which would have automatic change-over to spares for maintenance.

All these objectives are incorporated in the LOG report of June 1984 and further described in the TAT-8 DCMS invitation-to-tender document which was issued on 1 February 1985.

Fundamental Interworking Requirements

TAT-8 will be used extensively for public telephony. Consequently, three fundamental requirements have to apply to enable North American and European public switched telephony networks to be interconnected for transmission: interface conversion, time-slot interchange for hierarchical conversion, and PCM standards conversion.

Interface Conversion

The lowest multiplexing order for TAT-8 will be 2 Mbit/s. The 2 Mbit/s digital path, which will be bit sequence independent, will form the bearer between the North American and European DCMS terminals. Manufacturers of the DCMS have recognised the advantages of designing a bearer which retains the CCITT Recommendation G.704 frame structure, with time-slot 0, for testing and maintenance purposes.

This bearer will connect two DCMS terminals, one having a 1·5 Mbit/s trunkside interface in North America and the other a 2 Mbit/s trunkside interface in Europe (Fig. 1).

For current CMS, the bearer capacity can be increased or decreased on an individual circuit basis to allow operation at advantages between 2:1 and 4:1; obviously the advantage used is dependent upon trunkside circuit activity and time-zone differences between trunkside routes connected to the one CMS. A fixed 2 Mbit/s bearer capacity for the DCMS makes this impossible; consequently, facilities for increased circuit multiplication advantages must be provided on the trunkside.

For a 5:1 multiplication ratio, the DCMS would operate at approximately 150/30 (2 Mbit/s bearer). But with a 150 circuit trunkside capacity, there is no direct relationship between the capacities of 1·5 Mbit/s and 2 Mbit/s systems.

The LOG decided that multiplication ratios up to 8:1, 240/30 (2 Mbit/s), could be realistically used on routes exhibiting time-zone busy-hour differences between the various trunkside circuit routes. The average overall circuit activity should remain low on the DCMS trunks where such time-zone differences occur. Therefore, the technical requirements stipulated a trunkside capacity of up to 8 × 2 Mbit/s ports or 10 × 1·5 Mbit/s. Routes with coincident busy-hours would probably be operated at ratios of approximately 150/30, in which case terminals would be equipped with five, six or seven 1·5 Mbit/s or 2 Mbit/s trunkside interface ports, as necessary, and some redundancy in trunkside systems would be tolerated.

Time-Slot Interchange

The second fundamental requirement was for any time-slot in any T1 1·5 Mbit/s digital stream to be connected to any time-slot in the CEPT 2 Mbit/s trunkside digital streams at the distant end, and vice versa. A time-slot interchange mapping function was included in the technical requirements for this purpose (Fig. 2).

PCM Standards Conversion

The third fundamental requirement was for μ-/A-law conversion between the T1 1·5 Mbit/s and CEPT 2 Mbit/s networks respectively. It was here that the DCMS could offer significant interworking advantage by utilising any μ-/A-law conversion facilities inherent in the low rate encoding (LRE) which would be used in conjunction with the DSI to provide 5:1 overall multiplication. Adaptive differential PCM (ADPCM) appeared the most likely LRE to be used since the CCITT was entering the final stages of testing and agreeing Recommendation G.721 for 32 kbit/s ADPCM whilst LOG was drafting the DCMS statement of requirements.

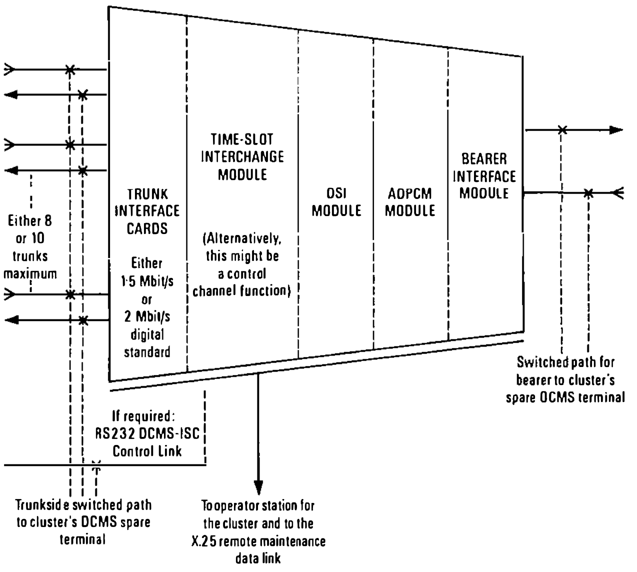


Fig. 2—Constituent parts of a typical DCMS terminal

A feature of ADPCM is that a signal input as either A- or μ-law PCM at one end can be recovered as either A- or μ-law PCM at the distant end.

The fundamental requirements for the TAT-8 DCMS described above and listed below are shown diagrammatically in Fig. 2:

(*a*) 1·5 Mbit/s or 2 Mbit/s trunkside interface;
(*b*) time-slot interchange for hierarchical repackaging;
(*c*) DSI for approximately 2·5:1 advantage; and
(*d*) LRE (for example, ADPCM) for 2:1 advantage and μ-/A-law conversion.

Traffic Carrying Requirements

As stated earlier, the DCMS would have to provide transparency for newer services and network requirements not yet fully defined or in operation. Even providing facilities for current services presented problems since some network operators permit services which others restrict, or actively sell customer equipment which exploit a current network transparency usually achievable but not guaranteed.

It was decided that three levels of DCMS transparency would be required:

(*a*) 64 kbit/s clear channel;
(*b*) 2:1 (that is, 32 kbit/s) for voiceband data; and
(*c*) 5:1 for speech.

Any variable bit-rate graceful overload which the DCMS might employ would be applied to the speech services only.

More interest is currently being taken in the traffic carried by public telephony routes. Fig. 3 shows an example of measurements made and illustrates the relationship between route capacity, speech and voiceband data. These measurements, taken at hourly or minute intervals, indicate a higher level of voiceband data than was earlier thought to be present and higher than that assumed when earlier CMS were designed. Although the voiceband data component has not been analysed in detail, a high proportion of it is believed

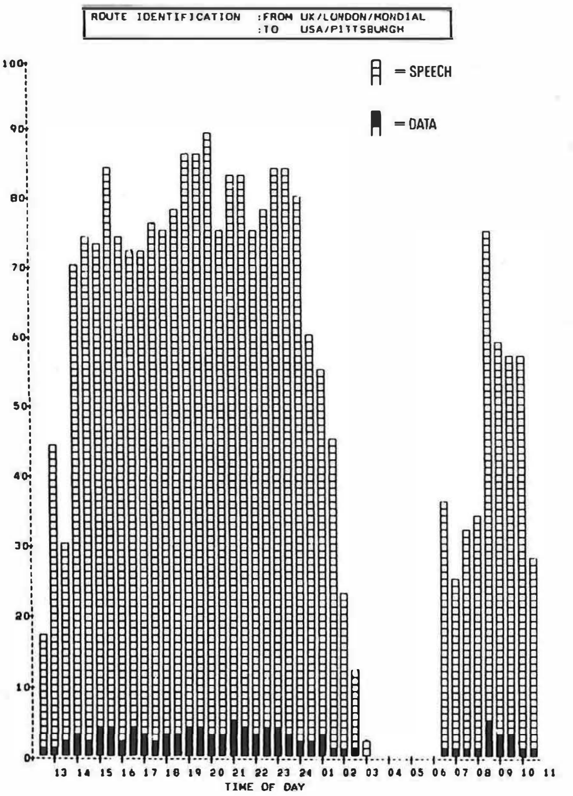


Fig. 3—Example of a speech/data traffic profile

to be from facsimile machines working at data rates up to 9·6 kbit/s in the V.29 mode. Small sample surveys by manufacturers of facsimile machines and others had recently indicated that 80–90% of international facsimile calls were successfully transmitted at data speeds above 4·8 kbit/s. The CCITT G.721 32 kbit/s ADPCM was already attracting interest as a possible LRE for the DCMS, but was known to have limited capability for passing data. Many members of the LOG stated that G.721 would be adequate for their purposes, although it would not pass data rates above 4·8 kbit/s. They saw no reason for preserving higher rates since these were not guaranteed. Some had definite reasons for requiring transparency to 9·6 kbit/s V.29 data and this requirement was carried forward on an option basis to the TAT-8 DCMS invitation to tender.

There has been much discussion in the CCITT and other fora regarding the necessity to preserve 9·6 kbit/s V.29 transparency in the medium term. There was no universal agreement on the subject, but it was regarded as important enough for DCMS tenderers to offer the facility. Independent tests had claimed that the 9·6 kbit/s capability could be preserved through both 4 bit and 5 bit ADPCM and, consequently, there was confidence that the requirement could be met realistically.

Exact traffic carrying requirements for the TAT-8 DCMS could not be stated since traffic profiles, busy-hours and other factors are very route dependent. Many CMS used on North Atlantic routes generally record a maximum busy-hour system speech activity, averaged across all trunk inputs, of 33%. Often the activity is around 29%. Some network operators have CMS which record system speech activities up to 37% on North Atlantic systems. Dial-up voiceband data on routes often averages 7% and peaks to 15% of route capacity and must be considered in conjunction with the speech activity. Speech activity and dial-up voiceband data are measurable and relate to present network services; however, the DCMS will not be brought into service until mid-1988 and should remain in operation for at least 10 years. It is probable that ISDN services will be introduced at the end of the decade and the DCMS should incorporate a traffic carrying allowance for 64 kbit/s services. As it has not been possible to be exact about required traffic loading figures for the DCMS, the potential manufacturers were requested to indicate the traffic carrying capacity of their systems for comparison against guide figures. Practical experience indicated that the DCMS should be capable of carrying in total 2 × 64 kbit/s clear-channel circuits, 7% voiceband data and the remaining speech circuits at up to 33% activity, or 37% activity speech and 5% voiceband data with no 64 kbit/s clear channel capacity. Since the speech activity figure is statistically derived, the DCMS should be able to accommodate a distribution, although this might lead to a small percentage of overload working.

The ability of the DCMS to accept per-call 64 kbit/s clear-channel requirements for ISDN etc. would also place a heavy instantaneous traffic loading upon the system. It was decided that dynamic load control (DLC) facilities busying-back to the international switch and preventing further access to the DCMS would be too slow to avoid unacceptable degradation to speech circuits as a result of freeze-out. A graceful overload strategy would be preferable.

Graceful overload methods which concentrated on the ADPCM and entailed a reduction from the normal four bits to three, or even two, had been independently researched and found subjectively acceptable for speech by Bell Laboratories, British Telecom Research Laboratories and CNET†. It was decided that tenderers for the TAT-8 DCMS should be free to offer such graceful overload facilities if they felt able.

The ability of the DCMS to accept 64 kbit/s calls on demand and the consequent handling of any overload by variable bit-rate ADPCM will be critically examined during prototype testing of the first DCMS in early-1987.

Apart from per-call 64 kbit/s access, a definite requirement is materialising to route CCITT No. 7 signalling links through the DCMS on a permanent basis to North American gateway switches. The CCITT No. 7 signalling links require bit sequence independent 64 kbit/s paths between exchanges and, since the North American network is not extensively bit sequence independent at rates above 56 kbit/s, routings through the DCMS would appear, at present, to be the simplest way to achieve direct 64 kbit/s routings to international gateways embedded in the North American network.

A third requirement for 64 kbit/s bit sequence independent permanent circuits could be for leased services. A limited number of these could be routed through the DCMS. However, heavy loadings of 64 kbit/s and voiceband data services will reduce the DCMS ability to achieve an overall 5:1 multiplication ratio and necessitate changes in the route dimensioning.

NETWORK OPERATION OF THE DCMS

Traffic Management

Telecommunication networks are experiencing a transition from a state where analogue transmission systems have been predominantly used for speech to one where digital transmission systems are being rapidly introduced, and there are greater demands for more versatile transmission capabilities to accommodate sophisticated customer equipment.

To cope with the above, the DCMS has been required to offer enhanced traffic-management and load-control facilities, if required. Two features have been extended when compared with present CMS: one is the selective traffic

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† CNET—Centre National d'Etudes des Télécommunications (French PTT research establishment in Paris and Lannion, France)

management (STM) facility, and the second is for a greater range of controls between the DCMS and the international switch (DCMS-ISC control link). The current practice of having a control terminal close to the CMS for control purposes would be basically continued. The DCMS could be provided with an operator station video display terminal (VDT) on an individual or cluster basis for local control purposes. For those users requiring more centralised remote maintenance facilities, an X.25 data link facility would be provided. In addition, an on-equipment control panel option has been included in the requirements for those users wishing to operate systems in a simpler, discrete equipment manner.

Selective Traffic Management

Possibly, demand for 64 kbit/s and voiceband data services might be heavier outside the speech busy-hours, but it is certain that demand for 64 kbit/s services especially would have to be restricted to a maximum during the busy-hour. To accommodate this possibility, the DCMS would be equipped with STM facilities so that 64 kbit/s access etc. could be restricted to thresholds at predetermined times during a 24-hour period. Obviously the number of on-demand 64 kbit/s circuits that could be accommodated would depend upon overall speech activity likely to occur on the system at any one particular time. During the busy-hours, with approximately 29–33% speech activity and up to 7% voiceband data, it might be necessary to limit the total 64 kbit/s capacity to two or three calls. If the DCMS were carrying a CCITT No. 7 signalling link and a 64 kbit/s leased circuit, it might be necessary to prevent 64 kbit/s on-demand access during the busy-hour, but allow unrestricted access during known quieter times.

At some future date, it might be necessary to apply a maximum capacity threshold to voiceband data during busy-hours, in order to preserve speech circuit capacity, by allowing DCMS access to a predetermined number of 2100 Hz identified data calls. At present, this is only a matter for consideration, but it would be an STM implemented facility if required.

Selection of the STM functions would be achieved by using the DCMS VDT operator station associated with either single terminals or the clusters of seven to eight working terminals with spare and change-over switch.

The ability to select STM functions must be translated into control signals between the DCMS and the international switch—hence the enhanced DCMS–ISC control link.

DCMS–ISC Control Link

Current CMS have a simple dynamic load control (DLC) from the DCMS terminal back to the switch. When the CMS detects concentrated freeze-out, it sends a BUSY BACK condition to the switch to prevent further access to the system. The CMS does not control its load since the concentrated freeze-out could continue until a call finishes. In addition, the CMS requires time to decide that the freeze-out has persisted above a threshold and that DLC application is necessary.

For the TAT-8 DCMS, a more responsive and comprehensive DLC facility was deemed necessary. Problems could arise owing to the higher multiplication ratio and, particularly, if 64 kbit/s on-demand access was provided which might push the DCMS more suddenly into freeze-out (since the one 64 kbit/s circuit would be the equivalent of five speech circuits). Variable-rate ADPCM graceful overload facilities would preserve speech transparency in the short term, but conventional busy-back DLC to the switch would still be required to guard against severe and/or longer-term overload.

The DCMS would be unable to refuse 64 kbit/s on-demand access as the call occurs because of the speed at which CCITT No. 7 signalling information is transferred between international switches. Consequently, it will be necessary to apply a longer-term DLC condition from the DCMS back to the switch, preventing further 64 kbit/s demand attempts, when a predetermined traffic loading threshold level has been reached. Therefore, either extra information and commands will have to be sent from the DCMS to the switch to continually update the latter regarding the DCMS traffic loading, or a dialogue of protocols between DCMS and switch will be required. Typical requirements for monologue or dialogue controls between DCMS and switch might be selected from those below:

(*a*) to indicate from the switch to the DCMS that a 64 kbit/s on-demand circuit is required and cannot be refused;

(*b*) that the DCMS has acknowledged and provided facilities for a circuit; and

(*c*) that the DCMS, having reached a threshold, cannot accept further 64 kbit/s or other call demands.

Some users will still require a basic DLC concentrated freeze-out busy-back to the switch, but others will require more comprehensive structures as described above. Suitable methods of implementation and command protocols by using either CEPT 2 Mbit/s time-slot 16, another time-slot, a T1 1·5 Mbit/s redundant time-slot, or an RS232 interface are the subject of current discussions in CCITT SGXI and with switch manufacturers.

Maintenance Support—Cluster Operation

Present use of CMS usually entails having identical terminals at each end of the route and using a 2:1 advantage. If a terminal fails, a relay by-pass arrangement can provide restoration for half the CMS capacity.

The TAT-8 DCMS could not utilise this method of failure support owing to the hierarchical and PCM standards differences at each end of the route. In addition, the 5:1 multiplication would mean 20% restoration only.

The technical requirements asked tenderers to consider failure switching to redundant spares as a method of supporting working terminals. Manufacturers have offered switching whereby seven or eight working terminals could be associated through a matrix with one spare. The combination of workers, spare and matrix has been termed a ***cluster***. Each cluster would have its own operator station for all operations and maintenance control. The working terminals in the cluster would be equipped with non-volatile memories so that their configuration information can be transferred to the spare upon switchover. The objective would be to bring the spare into service with the minimum start-up delay.

The DCMS will provide the usual management statistics associated with CMS usage; for example, speech activity etc, and all the usual configuration controls. These will be supplemented by information associated with digital network management and the time-slot interchange functions mentioned earlier. This information will be output at the operator station together with the alarms and operating conditions applicable to each cluster.

THE TAT-8 NETWORK CONFIGURATION FOR DCMS

The LOG studied the possible global configuration and likely locations for DCMS installation. The basic ideal considered was that the DCMS should be sited as closely as possible to its parent international switch and, if not with the switch, at the extreme end of the digital network penetration from the TAT-8 cable heads so that maximum transit cost benefits could be obtained.

It was recognised that many users would have initially to access TAT-8 by using analogue systems. In these instances, DCMS would be located at the nearest convenient digital extremity from TAT-8 and be used to collect traffic from the analogue systems—the collecting point DCMS concept.

All systems will require a 2 Mbit/s bearer between terminals; therefore, the lowest order 2 Mbit/s from TAT-8 will have to be extended bit sequence independently into the European and North American networks. Since 2 Mbit/s is a standard hierarchical level in Europe, no problems are anticipated for Eastern partners to the TAT-8 project. In North America, the 2 Mbit/s bearers will have to be carried into the network on 6·3 Mbit/s digital paths. This does mean that careful route dimensioning will be required to the North American switches since 3 × 2 Mbit/s can be accommodated on one 6·3 Mbit/s digital path, and it would be preferable for all three to be used since spare 2 Mbit/s capacity will probably be unusable in the normal North American network. Also, it will not be possible to mix 2 Mbit/s and 1·5 Mbit/s digital streams in one 6·3 Mbit/s. North American carriers intend to route capacity inland from Tuckerton to their ISCs by using either 6·3 Mbit/s or 45 Mbit/s facilities. Typical locations for the DCMS terminals will be New York, Montreal and Atlanta.

The French PTT intends demultiplexing the TAT-8 hierarchy at the landing point, Penmarch, and converting to the CEPT hierarchy for transmission through France to Paris and Marseille, the main centres for DCMS location.

BTI will route TAT-8 capacity at 140 Mbit/s from its landing point, Widemouth, back to London for demultiplexing and conversion to the CEPT hierarchy. The DCMS will be located in London.

Several Eastern parties will have 2 Mbit/s bearer capacity routed through France, the UK and other countries to their own DCMS installations at their international switches, embedded in several European networks many hundreds of kilometres from the TAT-8 cableheads.

DCMS PROCUREMENT

Liaison and Operations Group

The procurement process started at the planning stages for TAT-8 itself when the LOG forum was established as mentioned earlier. The LOG drafted the original statement of requirements for the TAT-8 DCMS. The statement of requirements was handed on from the LOG, when the contracts for TAT-8 had been signed, to TAT-8 Sub-Committee A, which is responsible for the networking aspects of TAT-8 use.

TAT-8 Sub-Committee A

Recognising that cost economies and operational advantages could accrue if a joint DCMS procurement exercise was mounted, the TAT-8 Sub-Committee A established the DCMS procurement working party in October 1984 under the chairmanship of AT&T. Membership of the working party was open to members of Sub-Committee A, and membership comprised, AT&T, BTI, DBP, France PTT, Italcable, MCII and Teleglobe. These members would pursue tender invitation and evaluation on behalf of other TAT-8 co-owners with the objective of recommending the system or systems which would be most suitable

DCMS Procurement Working Party

The working party adapted the LOG report DCMS statement of requirements to incorporate the specific requirements of the member administrations and companies. More detailed requirements were added and reference material supplied so that the LOG document became the technical requirements.

The working party additionally drafted a price schedule covering the possible options which might be required and asked for quotes against different quantities of terminals. Example quality assurance requirements and commercial conditions were also included. Neither of these latter documents could be specific since the intention was for each purchaser to procure the terminals they required under the terms of their own national contracts. At least the example documents served to provide an idea of the commercial terms which would apply so that prices could be more realistically quoted.

The commercial conditions contained a very important requirement regarding the prototype. It allowed the DCMS contract to be declared void if the prototype failed to meet the test requirements as outlined in the LOG statement of requirements and carried forward to the invitation to tender.

The working party issued the invitation to tender on 1 February 1985 and stipulated return of tenders on 30 April 1985.

Tender Evaluation

Four tenders for three different DCMS designs were received after a total of 18 companies had expressed interest and received copies of the invitation to tender.

The working party decided that all tendered designs broadly complied with the technical requirements and, consequently, the preferences of the various users would have to be decided bilaterally according to commercial considerations and technical preferences.

All tendered systems had advantages and disadvantages which tended to polarise the selection of equipment. Owing to this, two tendered designs have tended to be preferred for different reasons.

Selected Systems

CIT-Alcatel offered a CELTIC 3G. This system uses common-channel 32 kbit/s signalling between terminals for assignment information and variable-rate ADPCM for short-term graceful overload. A 5 bit ADPCM facility has been offered for 9·6 kbit/s V.29 data transparency. Design work on the CELTIC 3G appears to be well advanced.

ECI offered a DTX-240. This system uses a distributed assignment signalling method between terminals and offers an option for variable-rate ADPCM graceful overload. A 4 bit ADPCM facility has been offered for 9·6 kbit/s V.29 data transparency. The 4 bit ADPCM for data offers advantages for system loading, but increases the development work outstanding with regard to this system.

PROTOTYPE TESTING

Invitation To Tender

The technical requirements of the invitation to tender included an annexure outlining the various test expectations for the DCMS. The annexure regarded the CCITT Recommendation G.113 provisional planning rule for 14 overall quantisation distortion units in an international connection as the main criterion against which the DCMS would be tested for speech quality. The annexure also stated that such speech quality testing would be carried out by using mean-opinion-score (MOS) methods. In addition to the speech quality tests, the DCMS would also be tested for data transparency.

The testing would also cover the DCMS capability to operate under errored transmission conditions and when in tandem with other systems which might employ LRE techniques.

Prototype Test Plans

The DCMS invitation to tender requested a prototype system for testing from 31 December 1986. Therefore, it is expected that prototype systems will be tested during the first six months of 1987.

It is anticipated that prototype testing will encompass three distinct phases:

Phase 1: Objective testing of the system Probably two terminals back-to-back. This testing would check such points as propagation delay, data transmission, signal recognition etc.

Phase 2: Subjective testing under controlled conditions This would probably entail installing two terminals in distant locations connected by a terrestrial digital facility. The terminals would be loaded with traffic simulators and loop-back paths provided to testing booths in research or similar establishments. By this means 'no mental effort' type subjective tests could be conducted over both the DCMS route and control route. The results would enable a mean opinion score comparison to be made between the DCMS route and a known control group route into which a number of PCM asynchronous tandem connections could be introduced.

Phase 3: Subjective testing in the network This would use ringback methods and customer interviews, and again would enable a mean opinion score comparison to be made between a control group route and the DCMS route.

The prototype testing would also check the operator station facilities and the ability of the change-over system to protect service.

PRESENT POSITION

The TAT-8 DCMS project has entered the design and manufacture stage. The next major objective will be the successful testing of the prototypes. It is anticipated that the future requirements for DCMS could increase with the wider use of digital facilities both terrestrially and via satellite such that there is every possibility future networks will be tandem operating DCMS as a standard networking measure.

Biography

Derek Cotterill joined BT as a Youth-in-Training in the Oxford Telephone Area in 1960 and subsequently worked in Oxford Repeater Station. During 1966/7 he worked for Bell Canada on transmission maintenance in Toronto Toll Area. After returning to circuit provision duties in the Oxford Area, he moved to Open Competition training at Horwood House in 1971. He joined BTI in 1977 and was engaged in submarine cable system planning until 1981 when he moved to international network planning.

Maintenance of Submarine Systems

Part 1—Terminal Station Maintenance, Cable Fault Location and Repair, and Maintenance Economics

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UDC 621.315.28 : 621.391.63

This article considers many of the problems and challenges facing the maintenance engineer in a new era, in terms of optical-fibre cables and greater cable protection through burial. Consideration is given to three elements by comparison with analogue systems: terminal station maintenance, cable fault location and repair, and maintenance economics. The first North Sea 280 Mbit/s repeatered system was laid and buried earlier this year, at a time when low-capacity analogue systems with a high fault liability are being recovered. The evolving new network of high-capacity optical-fibre cables will bring with it a new maintenance philosophy and new repair techniques.

INTRODUCTION

The introduction of optical-fibre submarine cable systems is the start of a new era from a maintenance viewpoint, not merely springing from the use of a new transmission medium and digital traffic, but in terms of a maintenance philosophy aimed at improved cable protection and higher cost effectiveness. The increased adoption of cable burial as a protection technique follows the development of the heavy rock-armour cable, both of which were tried and tested on the later analogue systems. The cable protection philosophy for optical-fibre systems will be to adopt burial wherever possible and to use rock-armour cable where burial is impractical or in areas of shifting sea-bed conditions. This approach to cable protection requires more sophisticated ship-stationing equipment, more accurate cable location for repairs, the use of submersibles for reburial after repair and possibly for surveying the cable prior to recovery from the sea bed. These and many other aspects of repair techniques and procedures are under active consideration for both short-haul and inter-continental systems.

The following paragraphs describe some of the maintenance problems which have been addressed and the decisions made by British Telecom International (BTI) and the other co-owners of the systems due to be installed in the near future.

TERMINAL REPEATER STATION MAINTENANCE

Details of the hardware and operation of the digital terminal station are given elsewhere in this *Journal*[1]. The important aspects from the maintenance viewpoint are the ability to monitor the performance of the system, to locate faults on the equipment and make them good, to locate faults on the submerged plant from the terminal station, and to provide adequate power-feeding arrangements.

Faulty units within the terminal are identified by alarm display panels which can be interrogated both locally and remotely by using a telemetry channel. Each equipment card has monitoring points for both clock and data at the input and output stages. For the purpose of detection, a frequency counter is used for the clock signals and an oscilloscope for data. Injection of an *alarm indication* signal (AIS) suppresses all subsequent alarms to aid in the identification of faulty cards. Unlike analogue system practice, spare cards are kept powered and maintained on an additional equipment rack. Although this rack cannot be used to replace one of those operating to line, the cards can be used to substitute suspect cards in the operating equipment. Faulty cards can then be sent to a repair centre for attention.

As with analogue systems, there is submerged repeater monitoring equipment (SRME) that can communicate with the repeaters, including in-service monitoring, such as laser threshold current. Should there be a system fault on the submerged plant, the SRME is used to locate the repeater section in which the fault has occurred. This is achieved with the system out of service by looping back the send and receive paths of each repeater in turn. It is also possible to check received light levels while the repeaters are looped back to the terminal. This is the first means of fault location used by terminal staff for submerged plant; refinements of the initial tests are discussed further in the section on cable fault location and repair. The full range of tests available with the SRME varies according to the system; those used on the UK–Belgium No. 5 and TAT-8 systems are given in Table 1, some of which can be conducted with the system in service.

TABLE 1

Submerged Repeater Monitoring Equipment (SRME) Tests

SRME Test	UK–Belgium No. 5	TAT-8
Laser Health	In-service	In-service
Received Light Level	Out-of-service	In-service
Loop-Back	Out-of-service	Out-of-service
Error Monitoring	Not available	In-service
Laser Switching	Not available	In-service

Because of the short length of the UK–Belgium No. 5 system, it was not considered necessary to engineer the system to give error monitoring at the repeaters or to build laser redundancy into each repeater, with switching from the terminal. Redundancy exists through the provision of three fibre pairs.

The SRME and the terminal alarms are both linked to the computerised instrument control unit, which has data storage facilities. This permits automated equipment routines and data storage, a practice which was developed in the later years of analogue systems. Data can then be analysed on site or transmitted to a central location for later analysis.

For both long-haul and short-haul systems, the approach to maintenance will be very similar; one exception, however, is that the terminal transmission equipment will be duplicated for long-haul systems, with a main and stand-by unit.

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This practice differs from the latest analogue systems, in which only the wideband equipment is duplicated, with a change-over switching facility.

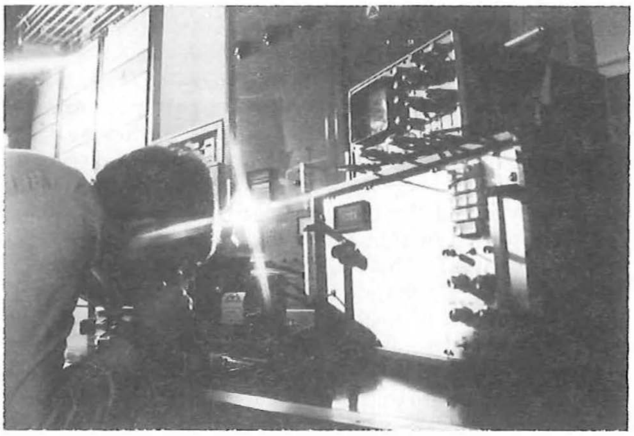
Practices for the power-feeding equipment will also be similar to existing analogue systems: stand-by units will be used at each terminal, with hot transfer on long-haul systems. The complexities of power feeding on a system with branching units, which are discussed elsewhere in this *Journal*[1], create an even greater need for awareness of the hazards of power feeding and the observance of the safety regulations by terminal station staff and ship's personnel.

CABLE FAULT LOCATION AND REPAIR

Once a fault has been identified as being within a repeater section by means of the SRME, more accurate location can be made by using additional testing equipment, either from the terminal station or cable repair ship. Discontinuities and damage to fibres, such as faulty splices, can be checked by means of an optical time-domain reflectometer (OTDR) set, which operates on the same principle as the pulse echo equipment used on analogue systems. A pulse wave at light frequency is propagated through the fibre to detect any breaks or imperfections in the transmission path. Such anomalies cause a reflection which is detected by the OTDR set, in addition to reflections from the fault. Because of the low level of the reflection, analysis is also based on reflections from cable imperfections (Rayleigh scattering), which are considered to be evenly distributed along the cable length to the fault. The distance to the fault is a function of the time between transmission of the signal and receipt of the reflected pulse, given the speed at which the signal is propagated. Currently, OTDR sets can be used on only the shore-end sections and for testing within a section from a ship after a cable has been cut. Proprietary equipment has a limited range, but a test set with an extended range suitable for a whole-section length has been developed by British Telecom Research Laboratories (BTRL).

It is normal to have available more than one method of testing cables for damage, particularly as such damage may be only to the power-feeding conductor, rather than to the fibres. The design of optical-fibre cables has resulted in different conductor parameters when compared with analogue cables, for which the testing techniques and cable specifications have been evolved over decades to optimise testing and fault location facilities. The complementary facilities on optical-fibre cables utilising electrical methods of fault location, including AC methods such as pulse echo, impedance frequency tests and traditional DC techniques such as conductor resistance and capacitance testing, will go through a similar process of refinement with time.

The cable repair ship will be able to locate the cable up to the fault by means of electroding. An electroding tone of 25 Hz is applied from the terminal station by modulating the line current from the power-feeding equipment. The ship detects the field created by the alternating current sent to line by trailing electrodes close to the sea bed and crossing the cable at right angles. The electroding signal was originally transmitted to line with the system depowered; however, in later years, systems were modified to permit 'in service' electroding, and it is this method which will be used on the optical-fibre systems. An additional constraint to testing the optical-fibre cable is the need for a DC plateau in the repeater to permit electrical tests, over which the DC resistance characteristics must be constant for a range of currents. This plateau has been reduced to meet other design considerations, and thereby the opportunity for electrical testing is limited.



Engineer operating an optical time-domain reflectometer on the UK–Belgium No. 5 system

Additional work will be undertaken to determine the best testing techniques, and whether the techniques can be enhanced by the improvement of existing equipment, such as the addition of an averaging device to the OTDR set to increase its range.

Where a repeater in an optical-fibre system is found to be faulty, the cable repair ship will replace it with a system spare; the repeater tails will need to be recovered as well and replaced by spares because of the possible stress during recovery. Both the repeater and tails will be then sent for repair and refurbishment as necessary. British Telecom has maintained full competence for repairing analogue repeaters, but this may not be practical with the high level of circuit integration characteristic of optical systems, and repairs may be limited to the module level, modules being returned to the supplier for repair. However, facilities for testing and the replacement of tails onto the repeater will be acquired by the maintenance interests.

Cable repair techniques need to be proven by repair simulations, and all suppliers have either completed or have scheduled repair exercises of this nature.

Shallow-water repairs in the North Sea and on the Continental Shelf will employ either the traditional method of grappling for the cable after location by electroding, or more sophisticated techniques such as the use of a submersible to locate the area of damage and its extent. The economics of the two options are discussed later in the section on maintenance economics. In either case, the ship needs to have available a detrenching grapnel as most cable will in the future be buried. On completion of a repair, it is proposed that cable will be reburied wherever possible. Associated with the problems of the preferred repair method is the decision on how much cable to insert into the system during a repair. Unlike analogue systems, the length of cable inserted is less critical to the cable-section loss than joint losses. Cable loss per kilometre is only 0·5 dB, whereas cumulative fibre joints may add up to 1·5 dB to the section loss. Care is therefore required when repairing sections which may have already been spliced in more than one place, as the ultimate penalty is a loss of traffic if the attenuation is too great on any one cable section. This differs from analogue systems where excessive loss on a section results in a noise increase and deterioration of the signal, but may not critically affect the ability of the system to continue to carry traffic.

In the past, damage to a cable has been plainly visible on the outer armouring or sheath, with continuity easily proven electrically. Unfortunately, it is possible for fibres to be stressed for some distance from the site of any visible damage and for further breakage to occur when the cable is returned to the sea bed, or at a later date, with no outwardly visible indication of damage. Stress affects are not visible or detectable by using an OTDR set; however, an appreciation of the extent of the latent defect could be determined by

(*a*) aerial observation from an aircraft immediately after the fault, to ascertain whether damage was by trawler or a large ship dragging its anchor; or

(*b*) by submersible inspection to study the disturbance to the sea bed and the quantity of cable dragged from the trench.

This enables a decision to be taken as to the extent of cable to be replaced.

Theoretical studies of fibre stress have been made by STC plc and BTRL, which in the main were in agreement, albeit the predicted extent of damage varied for the unburied cable. One encouraging conclusion from both reports was that buried cable suffered less fibre stress due to the drag exerted on the cable by the sea-bed material.

It remains for the cable owners to determine a policy on replacement of cable during a repair which is both economically and technically sound. For this reason, the repair method which utilises a submersible for inspection is the preferred option during the early years of optical-fibre systems. This will enable all interested parties to study the effects of external damage by trawlers and ship anchors and glean as much information as possible.

MAINTENANCE ECONOMICS

Attention to cable protection, while increasing the capital investment at installation, has resulted in reduced faults on the rock armoured and buried sections. Conversely, while there is less likelihood of damage, repairs are more expensive for buried cables when account is taken of the recovery time and need for reburial.

The philosophy of running cable ships as an insurance policy, utilised solely for maintenance of cables, is an outdated approach, as is retaining low-capacity high-fault-liability analogue cables for the maximum period of their design life. Cost centres, such as maintenance units, need to maximise the utilisation of assets and to derive an income by marketing their services for alternative work. Similarly, the maintenance costs associated with small-capacity analogue cables may be avoidable where alternative routing is available in a high-capacity cable network such as the North Sea network. The introduction of 45 MHz analogue and 280 Mbit/s digital systems increases the opportunity for rationalisation and subsequent cost reduction, and thereby the contribution to telecommunications administrations which will ultimately benefit the customer. A subsequent reduction in fault-prone cables should therefore lead to cost savings and the redistribution of resources to income-earning undertakings.

To date, cable repair ships have been fully equipped to undertake analogue repairs in terms of both expertise and equipment. Acquisition was gradual as the network evolved, each new system tending to be a follow on from the previous generation. Optical-fibre systems have introduced the need for new cable jointing and testing equipment, new grapnelling equipment for buried cable, repeater testing equipment and a change in jointing skills and calibre of operator. In an era of maximum protection and, as yet, few systems, the ship owner has been left with the dilemma of how to finance the initial investment with limited opportunity for a return on capital. In such situations, an appropriate solution is that the co-owners should themselves finance the outlay to protect their interest, and store the equipment in kit form as part of an equipment pool.

It is expected that, because of the advanced cable protection techniques, there will be less risk of cable damage and hence little requirement for live repair work. There could well be a problem of retaining personnel and ensuring that those remaining in the jointing field do not lose their expertise through lack of practice. As with analogue systems, this can be overcome to a degree by refresher training courses, a programme of test joints and simulated repairs.

Another means of distributing repair costs between appropriate cable owners is through maintenance agreements such as the Atlantic Cable Maintenance Agreement or the North Sea Cable Maintenance Agreement, whereby cable owners pay an annual standing charge for cable repair work to cover the ships' fixed costs. In addition, charges are rendered to cable owners of faulty cables to cover running costs incurred during a repair.

Such agreements also make provision for improvement work to be undertaken to reduce fault liability, and thus minimise liability of interruption and improve the quality of service seen by the customers. This leaves one outstanding consideration—the economics of cable replacement and subsequent utilisation of spare cable. The spare cable for the UK–Belgium No. 5 system was purchased as one continuous length of rock-armour cable, for use as replacement during repair work for either buried or surface-laid cable. Rock-armour cable is expensive and hence stocks must be preserved as a further purchase from the contractor would be expensive because of the additional factory costs of setting up a production line for a small quantity of cable. In an earlier paragraph, discussion centred on the amount of cable to be inserted during a repair; it is not yet known in practice how much stress will be exerted on fibres if a cable is damaged by trawlers or by ships dragging anchors. For this reason, it has been suggested that cable replacement could be as much as 2–3 km either side of the damage for a surface-laid section of cable. From a maintenance point of view, this is uneconomical; however, if insufficient cable has been cut out, it could risk a future additional repair operation, at considerable expense.

A possible solution is that a submersible could be deployed to assess the extent of the damage to cable prior to recovery and further stress, and then a decision on replacement could be made which would minimise the depletion of stock.

CONCLUSION

This article has highlighted many of the novel maintenance aspects of optical-fibre submarine cable systems; philosophy and procedures are rapidly changing with the new technology. Much experience needs to be gained before the optimum procedures for system maintenance and repair can be regarded as finalised.

References

[1] MYALL, J. V. W. The Design of a Production Terminal Equipment for Digital Optical-Fibre Submarine Cable Systems. *Br. Telecommun. Eng.*, July 1986 (this issue).

Biography

David Spain is the Head of Submarine Cable Systems Operational Management Group and is responsible for the maintenance of the UK terminating systems. He started his career in 1967 in the Southampton Telephone Area working on the installation of non-director exchanges and exchange planning, before transferring to the Marine Services Division into the submarine cable repair unit. This was followed by London Headquarters appointments on submarine systems which included system planning, engineering estimating and financial control.

Maintenance of Submarine Systems

Part 2—Submersible Plant

W. GREENWOOD, B.SC., C.ENG., M.I.E.E.,† and C. J. ROGERS*

UDC 621.315.28 : 621.391.63

This article considers the maintenance of submerged plant. It examines the various reasons for submarine cables being damaged, reviews the facilities and procedures for repairing them and gives an insight into the additional challenges created by the introduction of optical-fibre technology.

INTRODUCTION

Submarine cables have played an important role in international communications for over a century and, with the introduction of optical-fibre technology, are assured of continuing to do so. Consequently, the ability to repair faulty systems efficiently and speedily will continue to be of importance.

This article presents a brief summary of maintenance considerations for submerged plant, including a discussion on the various causes of cable faults, a review of the repair facilities and procedures, and an insight into the additional challenge which optical-fibre cable technology presents.

SYSTEM FAULTS

Submarine cable systems are specifically designed and manufactured to operate efficiently for at least 25 years, and, as such, a great deal of attention and expertise is dedicated to ensuring the reliability and endurance of the system components. Whilst system failure due to equipment malfunction is a continuing possibility, it is the impact of the essentially hostile marine environment upon the submerged plant which has caused most concern. Even a century ago, when cable materials and manufacturing techniques were at an early stage of development, the occurrence of a cable system failure without some physical disturbance to cause it was rare. Then, as now, system interruptions were mainly caused by human activity such as fishing, or to a lesser degree by some upheaval of nature such as submarine seismic activity, and only rarely by material defects.

Those rare system faults attributable to material or workmanship defects are not discussed in this article. However, environmental causes of faults, by far the major contributor, are as follows:

Fishing Activities

A submarine cable is clearly vulnerable to damage by fishing gear such as a trawl net being dragged along the sea bed. The principal hazard is presented by the beam, which is designed to keep the mouth of the net open, as illustrated in Fig. 1, causing damage as follows:

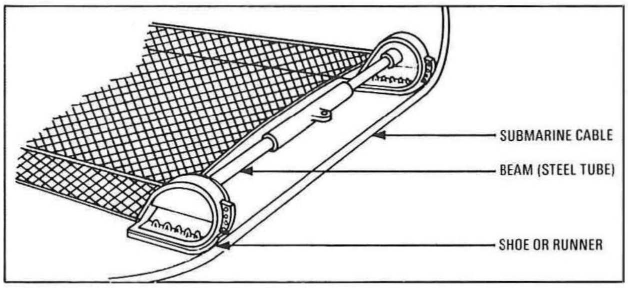


Fig. 1—Beam Trawl

(*a*) The heavy beam or shoe strikes and rotates the outer armouring of the cable, thus damaging the inner sheath and perhaps exposing the conductor.

(*b*) The beam or shoe becomes hooked under the cable, causing it to break under tension as the trawler proceeds on its way.

(*c*) The cable becomes hooked by the trawl gear, not parting under tension, but being raised to the deck of the trawler to be cut by the crew.

A great deal of research is being undertaken to produce trawls that do not damage or hook the cables, and some of the fishing boats which operate from the east coast of Scotland incorporate 'rock hopper' gear in their trawls in an attempt to reduce the risk of hooking underwater obstructions.

The cable is put at risk in any area where trawlers operate since the heaviest gear can penetrate the sea bed by as much as 40 cm and thus strike the cable. The modern beam trawler, with engines of up to 4000 horsepower, the capability to work in the severest of weathers, and equipped with very heavy trawls, is able to hook, pull and break some submarine cables without interfering with its fishing. The cable is further put at risk in areas of sand waves and substantial sea-bed movement, when the cable may be left in suspension and in greater danger of being hooked by a trawl.

Commercial Shipping Activities

In the same way that a fisherman's trawl gear can damage

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* Marine Services, British Telecom International

a submarine cable, a ship's anchor can drag over a cable and hook it, and this, in turn, can lead to serious damage necessitating repair. Anchors are specifically designed to penetrate and 'dig in' to the sea bed, and, depending upon the nature of the sea-bed conditions, can reach a depth of as much as 3 m, thereby constituting a particular threat to submarine cables even if deliberately buried at a depth of, say, 1 m to obviate damage by trawling.

The anchor itself may be dropped inadvertantly, perhaps owing to a failure in the securing mechanism, or deliberately in the event of engine failure or a similar emergency. There have been instances whereby major damage has been inflicted on closely adjacent cables by a single vessel; one vessel is known to have inadvertently dragged its anchor along the sea bed while on passage down the English Channel and seriously damaged three cables, and yet another vessel broke two cables when, in stormy weather, it dropped its anchors in an attempt to prevent itself being swept ashore.

Corrosion

Cables on some routes have a high proportion of faults caused by corrosion, with the probability that the incidence of faults from fishing activity is much higher when the cable armour is weakened by corrosion.

The cause of this corrosion is the electrochemical reaction which takes place when mild steel is in contact with aerated salt water. However, it is not fully understood why the galvanising, tar and jute protection which is applied to cables should last for 40 years in good condition in some areas, and only three or four years in others. One of the reasons for the long life of cables in some areas is the existence of sedimentary ooze on the sea bed, into which the cable sinks, and which excludes oxygen from the cable. Other areas are subject to fast tidal currents which appear to sand-blast the cable, scouring away the jute, bitumen and galvanising layer from around it, and exposing fresh metal to highly oxygenated salt water. The action of the fast running water also exposes bare rock in many places which can cause chafing of the cable against the rocks.

The repair of cables in these areas requires great care and skill in the handling of both the ship and the cables, since the tensile strength of the armouring is likely to be very much reduced in exposed localised sections, while being buried under tons of sand in closely adjacent sections. In these circumstances, the tensile strength of the corroded section may be lower than the forces required to retrieve the buried section, and this causes further breakages during the recovery process.

Other Causes

Very occasionally, other types of fault occur. There are several places on the deep ocean floor where volcanic activity takes place, damaging the cable. Earthquakes and other seismic activity can similarly give rise to cable damage.

On the edge of the continental shelf, it has been conventional practice for cables to be laid in valleys to go down the steep slope. It has however been determined that this is where the deep ocean currents tend to concentrate when flowing up the slope, and this causes chafing in some cases and, in others, a curious kind of fault in which the continual shaking of the cable has resulted in metal fatigue. The outer conductor breaks into hundreds of concentric rings, which sometimes touch and sometimes separate, causing electrical noise, the source of which is very difficult to locate to a particular point in the cable.

Occasionally, cable ships have recovered cable at a fault position to find that the cable has been severely crushed, with no clear indication as to the cause.

THE INTERNATIONAL CABLE PROTECTION COMMITTEE

The world's first submarine cable survived only one day before a fisherman hooked up what he may have thought was a new form of seaweed with a solid copper stem. Thus, from the very beginning, it was apparent that a strategy had to be developed to combat the threat from fishing and other marine activities. In 1884, 27 maritime governments met with 'the desire to secure the maintenance of telegraphic communication', and since then the world's cable owners have actively pursued methods of reducing damage to submarine cables.

The present organisation, known as the *International Cable Protection Committee* (ICPC), was formed in 1967. The ICPC maintains a global organisation dedicated to pooling knowledge and experience on cable protection matters and to publicising the presence, importance and value of submarine telecommunication cables by the dissemination of cable warning charts and other publicity and educational material to the fishing, shipping and off-shore industrial community in general. The various interested governmental organisations, such as the Ministry of Agriculture, Fisheries and Food in the UK, also complement these efforts by patrolling the main fishing grounds and ensuring, as far as possible, that fishing is not undertaken over known submarine cables and that offenders are identified. In common with many other ICPC members around the world, British Telecom (BT) has a policy of instituting legal proceedings for the recovery of costs and damages from any shipowner who deliberately or negligently damages a submarine cable.

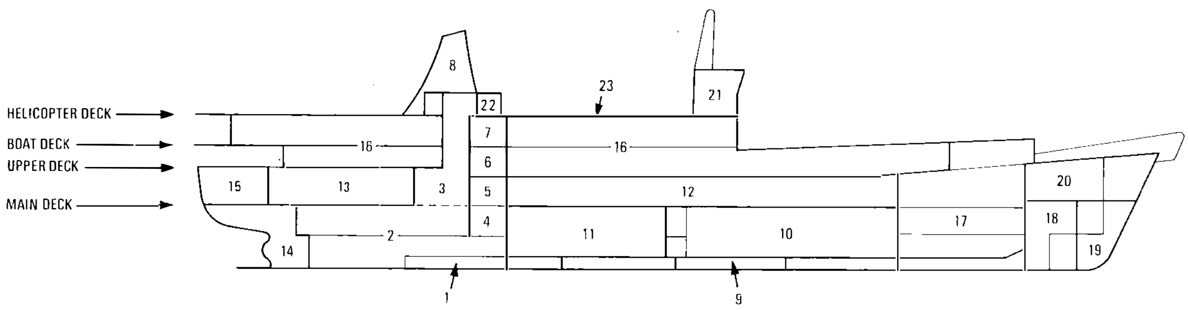
The ICPC, therefore, represents an important line of defence in the competition for sea-bed usage between the fishing and shipping industries and the telecommunications industry, a struggle that has continued for over a hundred years. Such is the sophistication of, and investment in, today's submarine cables and the increasing uses of the sea bed by the hydrocarbon and mining industries that more formal controls of sea-bed usage are now being looked for.

BT'S SUBMARINE-CABLE REPAIR FACILITY

Since the inception of submarine cables in the mid-1800s, the need for a comprehensive submarine-cable repair service has grown in importance, with today's high-technology cable design demanding a correspondingly technically advanced back-up service for all points of the world. For the UK, this is focussed at BT's depot in Southampton[1], equipped with every modern facility.

A major part of this repair facility is the BT fleet, consisting of three purpose-built cable ships: *CS Alert*, primarily employed in Atlantic operations, and the smaller vessels *CS Monarch* and *CS Iris*[2], see Figs. 2 and 3. In

Fig. 2—*CS Monarch*



Key: 1—Engine-room double-bottom tanks 2—Engine room 3—Engine-room casings 4—Engine-room control room 5—Engine-room boiler room 6—Engine-room stores flat 7—Emergency-generator room 8—Funnel 9—Double-bottom tanks 10—Forward cable tanks 11—Aft cable tanks 12—Main deck offices and workshops 13—Galley and refrigerated stores 14—Aft-peak tanks 15—Steering-gear compartment 16—Officers' and crew's accommodation 17—Fore-hold and cable-machinery spaces 18—Bow-thrust machinery spaces 19—Fore-peak tank 20—Capstan-machinery spaces 21—Bridge structure including radio room 22—Engine-room ventilation room and air-conditioning plant 23—Lifeboat deck

Fig. 3—Diagrammatical view of *CS Iris/CS Monarch*

addition to the cable ships, BT operates a purpose-built submersible Trencher and submersible plough system, details of which are given in an accompanying article in this *Journal*[3].

CABLE-SHIP OPERATING AGREEMENTS

The cost of providing and sustaining the capability of a cable ship to carry out the wide range of demanding tasks required of it represents a considerable financial burden on the ship operator. Aside from the additional running costs incurred during marine operations, the standing charges to be financed by the ship operator in respect of a ship, its equipment and crew and the associated depot and logistic support services together amount to several million pounds per year. On this basis, it would clearly not be economic for each of the large and increasing number of entities having an investment in submarine cables to own and operate a cable ship for the purposes of carrying out repairs. However, each such entity must ensure that adequate arrangements are in place for submersible plant to be repaired as and when required.

Accordingly, the cable owners in each of the main ocean regions have come together and have entered into cable-ship operating agreements whereby, on what amounts to an insurance-policy basis, they collectively and continuously support the provision and upkeep of a limited number of cable ships to service their combined needs.

The Atlantic Cable Maintenance and Repair Agreement (ACMA) has served the Atlantic Ocean region since the inception of the ACMA in 1976. Currently, BT and twenty other submarine cable entities around the Atlantic are party to the ACMA, which supports the availability of five cable ships based in strategic locations, including the BT ship *CS Alert*, normally based in Southampton. The terms of the ACMA provide for a co-ordinated and controlled programme of cable-ship availability whereby, at the discretion of the Management Committee, the ships can be released from their ACMA obligations in order to undertake other work. This reduces the costs falling on the ACMA parties, and ensures that at least the necessary minimum cable-ship coverage is available at all times to deal with any cable faults which may occur.

In April 1986, similar concepts were embodied in a North Sea Cable Maintenance Agreement (NSCMA), replacing the previous bilateral arrangements whereby cable repairs in the North Sea and English Channel area were undertaken by a BT ship, the *CS Monarch* or *CS Iris*, or by the *CS Peter Faber* (Denmark) or the *CS Directeur Generale Bast* (Netherlands). BT, as the major investor in submarine cable systems in the North Sea, took the lead in developing the NSCMA, to which all the cable owners in the area are party.

BT is also a major party in the SCARAB† Agreement, under which a consortium of five Atlantic parties maintain two submersibles SCARAB I and SCARAB II. BT has the major ownership interest in SCARAB I, whilst the complementary SCARAB II vehicle is wholly owned by AT&T-Communications. The SCARAB vehicles are an essential adjunct to the capabilities of the *CS Alert* and other ACMA cable ships in carrying out repair and maintenance improvement work on Atlantic cables, whether buried or surface laid, in depths of water down to 1800 m (1000 fathoms). The deep-water capabilities of the SCARAB I vehicle were demonstrated to the world during 1985 when the vehicle successfully recovered the flight data and voice recorders of the Air India aircraft which was lost off the Irish coast.

SUBMARINE CABLE REPAIR

The basic requirements of locating and recovering a cable in order to effect a repair have remained unchanged since the inception of the submarine-cable era, although the complexities involved have significantly increased with time as systems have been laid at ever-increasing depths, have become physically smaller, have been buried, etc; therefore, an ever-increasing sophistication in location and repair techniques has been required.

After the occurrence of a cable fault, it is necessary to assess the fault location, test the repair cable, ascertain prevailing weather and tidal conditions, liaise with coastguard, naval and traffic-control authorities and compile the necessary charting and reporting documentation. Only after these preliminaries can the cable-ship sail to the cable ground. The appropriate power safety control is instituted to avoid accidents during the ensuing repair operation, whereby the cable ship adopts sole authority for the application and removal of the power-feed supply to the cable.

A 25 Hz tone is applied to the system from the shore repeater station on the arrival of the ship at the fault location,

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† SCARAB—Submersible craft assisting repair and burial

to facilitate precise identification of the fault position by the use of sensors deployed from the ship. Having located the cable, the ship tracks along it until the fault is found. If the cable is buried at or adjacent to the fault, it may be necessary to employ a submersible such as SCARAB or the BT Trencher to unbury the cable by jetting away the sea bed to allow the cable to be cut and the cable end lifted on to the deck of the ship for testing. Should the tests reveal that this first cable end is clear of faults towards the terminal station, then the end is sealed, attached to a marker buoy and slipped carefully from the ship.

The other end of the cable is then recovered and tested and the exact position of the cable fault determined; this enables the cable ship to recover the faulty section of cable and store it in the storage tanks on board. Should the cable be physically undamaged, it is cut at the expected fault location and retested, a process which is repeated as necessary until the 'all clear' is given. When both cable ends test clear, the pre-checked length of stock repair cable is jointed into the system and the cable lowered carefully into the water before it is released by the ship and allowed to sink to the sea bed. The system is then powered and tested fully before the all clear is given. Finally, a submersible may be employed to bury the replacement cable.

As an alternative to the use of a submersible vehicle for recovery of a faulty buried cable, the recently developed BT detrenching grapnel and sensing sledge may be used. This method involves the application of a 25 Hz tone to the cable prior to dragging a large pronged detrenching grapnel and sensing sledge across the line of the cable. The sensing sledge detects the cable and warns the staff of the cable ship prior to it being acquired by the grapnel. The cable, securely hooked by the grapnel, is then hauled on board the cable ship for repair. This, however, is not necessarily acceptable for optical-fibre cables since, depending on cable design, the process of raising the buried cable up to the ship imparts some degree of strain to the fibres themselves.

OPTICAL-FIBRE CABLE REPAIRS—THE TIME FACTOR

A buried cable repair operation can, in the case of an optical-fibre cable, involve the repair ship being on the cable ground for up to three days in good sea and weather conditions up to the point of restoring the cable to use, with further time being required for the reburial operation; this can be compared with the repair of a coaxial cable which may require only one day because of the shorter recovery and less complex jointing operation involved. The additional repair time presently required for buried optical-fibre cables is a significant aspect in maintenance considerations.

An important factor in all marine repair operations is the interaction between the cable ship and its marine environment and the associated complications that may arise when an intricate operation from a moving platform vulnerable to the effects of the sea is undertaken, particularly under changing conditions. Essentially, the problem confronting the mariner throughout a repair is to maintain the cable ship in a constant position relative to the cable so that no undue strain is imparted to the cable and no kinks are formed.

In order to achieve the high degree of station-keeping required, cable repair ships are equipped with some of the latest aids in ship handling. BT's ships, for example, can maintain any desired position in tidal streams of up to 6·5 km/h (3·5 knots) and wind speeds of 50 km/h (27 knots). Nevertheless, along with every other cable ship in the world, they are affected by the prevailing tidal and weather conditions to a greater or lesser extent. The tides, particularly in the North Sea, can attain high velocities even under normal conditions and can determine in which direction the cable ship will lie. Complications arise when the tide turns, thus altering the heading of the ship in relation to the cable it is repairing; under certain conditions when the repair becomes protracted the ship may well swing three or four times, with the danger that damaging kinks or turns can be formed in the cable. Furthermore, UK waters are notoriously unpredictable from the weather viewpoint and the cable ship is exposed to the possibility of commencing the repair in fine weather only to be confronted with stormy conditions in the later and more critical stages of the repair.

Against this background, and recognising that the recovery and jointing of a buried optical-fibre cable can initially take two to three times as long as its coaxial cable equivalent, it can be seen that the extended period necessary for an optical-fibre cable repair has the effect of exposing the operation to an increased weather and tidal risk and, in consequence, an increased risk of incurring cable damage. To reduce this risk, constant attention is given to developing new cable handling techniques and improved ship handling machinery, which will reduce the significance of this time factor as experience and expertise are acquired.

CONCLUSION

Unless and until a maintenance-free environment is created for submarine systems, it is clear that a marine repair service will continue to be required and that the systems operator will be responsible for providing and funding such a facility. The advent of optical-fibre technology coupled with the increasing adoption of sophisticated cable-protection techniques has significantly increased the complexity and duration of repair operations. Hence, development is continuing in an effort to reduce this more closely to repair times achievable for analogue systems in similar environments.

Biographies

Bill Greenwood joined BT on a university scholarship scheme. Upon graduation with a B.Sc. degree in Electrical Engineering in 1966, he commenced work on the planning and contract supervision of trunk transmission systems projects. He gained further experience by being involved in the formulation of the BT network digitalisation policy and then led a telecommunications project in West Africa before joining the Submarine Cable and Microwave System Division. He is now Head of the Operations and Efficiency Section of the Satellite and Lines Executive and his responsibilities include the maintenance of the BT International submarine cable network.

Charles Rogers, who is a Master Mariner, joined the Post Office cable ships in 1974 as a Fourth Officer, having previously been employed as a Deck Officer with Shell Tankers (UK) Ltd. He has served on all three cable ships. While serving on *CS Alert*, the ship undertook a number of deep-water repairs, and SCARAB, the remotely operated vehicle, was deployed. In February 1984, he joined *CS Iris* as Chief Cable Officer/Relief Master until coming ashore in October 1984 to take up the post of Operations Manager.

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Optical-Fibre Submarine Cable Jointing

C. A. GOULD, B.SC., C.ENG.†

UDC 621.315.28 : 621.391.63

A number of optical-fibre submarine cable systems have now been laid. It is now pertinent to review the actions of cable manufacturers and system operators in relation to jointing. The system requirements, along with the cable design, specify the structure and processes required to manufacture a joint on board a cable ship. A marine joint requires new tools, procedures and tests to ensure satisfactory performance during the life of the system.

INTRODUCTION

Optical-fibre submarine cable has heralded the introduction of a whole array of new and different jointing techniques. However, submarine optical systems are designed to be mechanically compatible with the laying and repair equipment available on existing cable ships. By comparison with the existing method of jointing coaxial cables, the optical joint is completely different and requires more complex and rather more costly equipment than that used previously. The time taken is longer and more jointers are involved, working shifts in a team, yet with individual skills and tasks.

Because optical-fibre systems enable radically different solutions, new working practices are created. A sea cable joint can be considered not only as a fundamental repair tool, but also as a wet connection device between different cables, possibly from different manufacturers. Furthermore, it is the enabling device for branching units and is frequently adopted for land, beach and shore-end joints.

CABLE DESIGN

Optical fibres have relatively low intrinsic mechanical strength and typically withstand only 1–2% strain before break. They suffer from life degradation due to residual strain ageing, accelerated degradation due to the presence of sea water, and a worsening loss performance in the presence of hydrogen.

The cable has to be strong enough to provide protection against these hazards during laying, detrenching, recovery, and holding to a ship for repair. The static and dynamic operational strains must be minimised. Shallow-water, beach and terrestrial locations all require earth screening or differing layers of armour wires. For a regenerated system, there must be an insulated power-feed path through the cable with a low ohmic resistance.

JOINT DESIGN

Each optical-fibre cable manufacturer not only has a co-ordinated family of cables for a complete system, but also must have a series of cable joints. The degree to which the fundamental concepts of one particular cable joint is compatible with others in the cable range depends predominantly upon the ingenuity and foresight of the designer.

Clearly, the joint box used for repairing a sea cable that has incurred damage is as important as the cable itself. Thus an effective joint design reinstates all the vital properties of the original cable design with little or no degradation. All the structural parameters must be maintained, and the splice loss introduced into the transmission path must be minimal. There must be no loss variation when the cable is subjected to tension, pressure or temperature changes. Environmental conditions on a ship are far from ideal because of the vibration and swell. Without appropriate precautions, vibration can shake the fusion machine and cleaver out of adjustment. It is not unknown for the swell to affect the disposition of the operatives when they are peering into an inspection microscope. The humidity and airborne particulate matter are difficult to control. There are likely to be temperature variations and possibly considerable air movement. Often the space conditions are cramped and joints often have to completed within a weather window. As a result, some designers control the environment totally by means of containerised clean rooms, whilst others are more pragmatic and control carefully each aspect of the jointing operation. The most critical aspect is the fibre splice, so it is here that repeat operations must be tolerated. Therefore, in this respect, provision is made for storing spare fibre inside the joint housing. As the spare fibre is parent cable fibre, with the same initial proof strain value, the storage diameter must accommodate the susceptibility to static fatigue. The immediate fibre environment—air, wet or dry, jellies or oil—also has some influence. Storage diameters range typically from 40 mm to 80 mm and either run circumferentially or in the axial plane. The housing must be air and watertight.

JOINT CONSTRUCTION

The procedure for constructing joints varies considerably depending upon the cable design in question. In essence, the cable ends have to be prepared, the load transfer arranged, power-feed path connected, the fibres spliced, inspected and stored, and a pressure casing and insulation applied. For armoured cables, the armouring strength must be reinstated. At the junction of the rigid casing and the flexible cable, some form of bend restriction is normally applied; this also gives a smoother profile for handling the cable through ships' machinery.

CABLE PREPARATION

Firstly, the cable ends are prepared and, for armourless deep-water cable, this entails the measurement and marking

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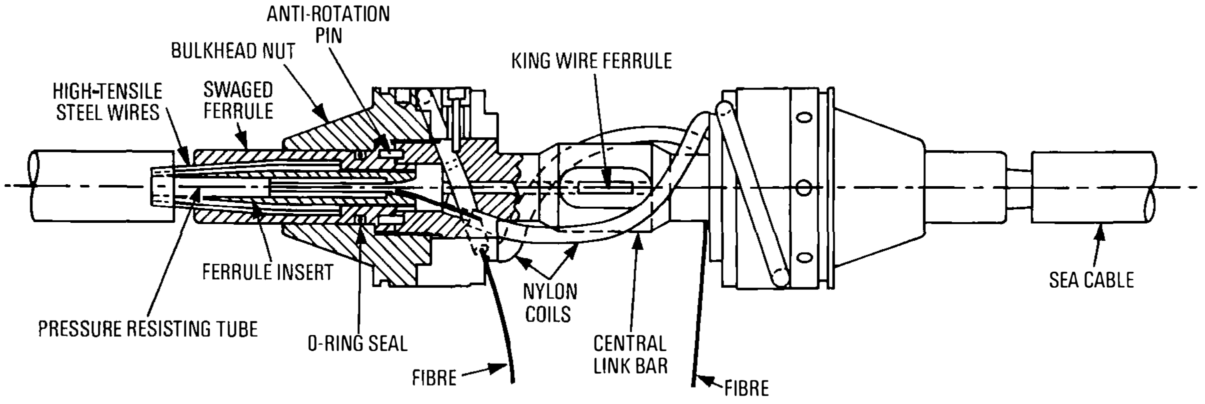
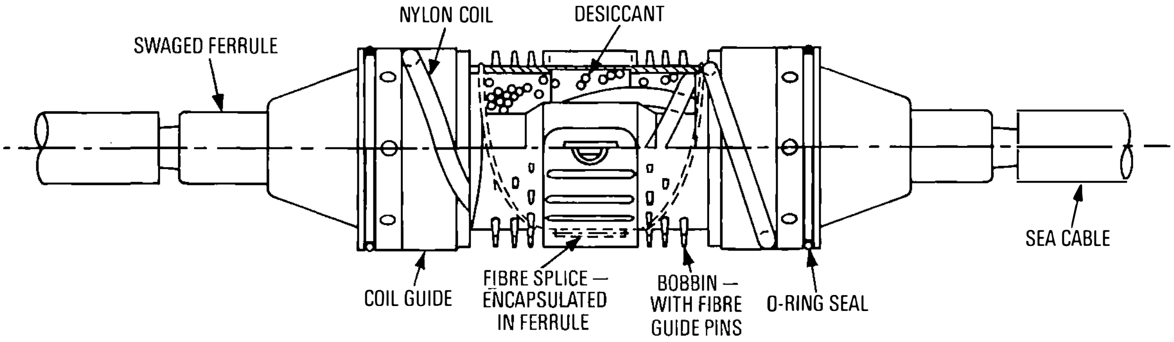
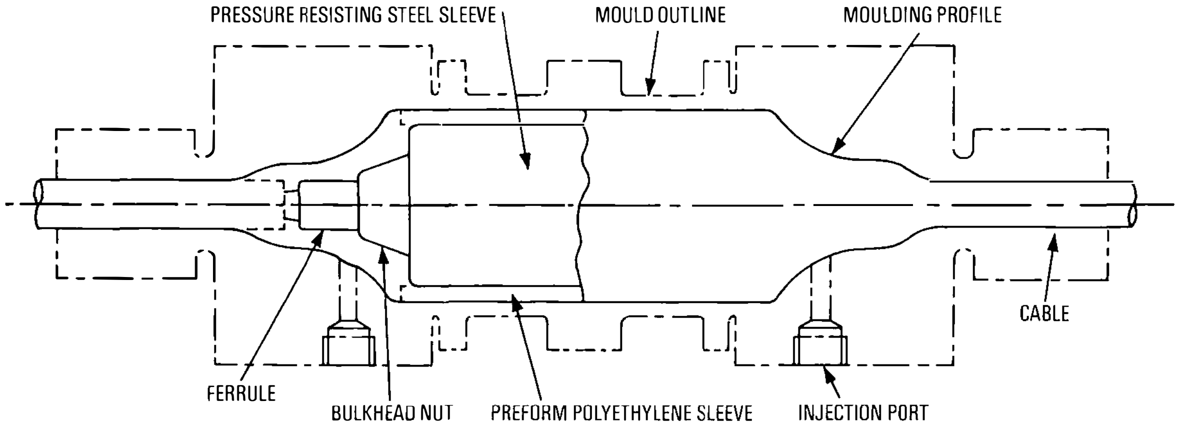


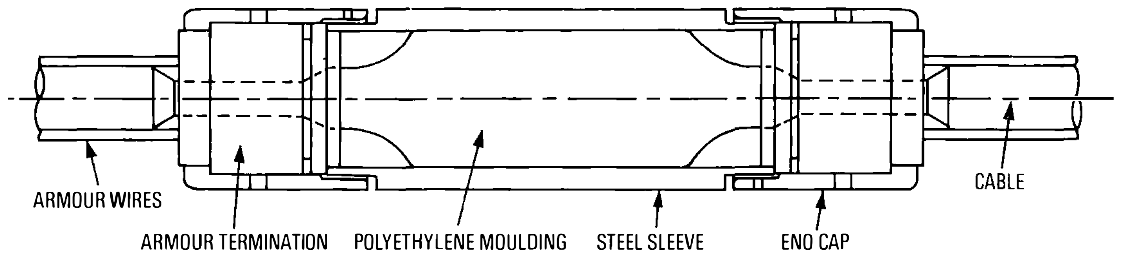
Strength member connection



Fibre splicing and storage



Joint in mould



Complete armoured cable joint

Typical features of an optical-fibre submarine cable joint

on the cable of the required working area. The outer insulation on the cable can then be removed, followed by the steel strength layers; this has to be done carefully in order not to damage the pressure-resistant tube. The pressure tube has to be cut to length very carefully, and generally by a partial depth circumferential cut; a discrete amount of flexural work hardening is used to effect separation. At various stages in the manufacture of the cable, various waterblocking compounds are included. These are removed either mechanically or by means of hot agitated chemicals. Some setting materials can be softened by electrical heating to reduce viscosity and aid removal. The fibre package and individual fibres can then be cleaned further in ultrasonic baths or by wiping with solvents.

Once the cable ends have been prepared, with all constituent parts made ready, the strength member strand is terminated in a pressed or swaged ferrule, sometimes gritted with silicon carbide. The choice of technique used depends upon the number of steel-wire layers, their size, helical lay direction and, in one instance, the use of shaped metal tapes. As the fibre package in most of the cable designs is run centrally within the pressure protection system, hardened hollow ferrule inserts are used to prevent the pressure tube from collapsing during swaging. For axial pressings, these tend to be a matching conical pair. For radial pressings, the insert and ferrule tend to be parallel. The press is either hydraulic and hand driven, or power assisted. By the use of either of these two techniques, over 90% of the parent cable strength is achieved. The conical system relies on friction of a soft metal such as copper, or a post pressing clamp with a screwed flange. The conical system is favoured for use with shaped steel-tape designs of strength member or for those containing metallic, say lead, tubes for fibre protection against hydrogen and sea water. Conical arrangements lend themselves to tandem terminations.

The system for transferring strength from one cable ferrule to the other is again achieved by one of two different techniques. Either the strength passes axially down the centre of the joint with a linking tie bar, or it passes via a supporting bulkhead collar plate to the joint containment and pressure tube. Whichever system is used, the ferrule is attached to a locking bulkhead collar to support the pressure tube. The pressure-resistant tube or housing, besides providing protection for the spliced fibres, also maintains a low-resistance power-feed path.

The prepared cable ends are then brought together, generally under the control of a hand-operated screw-driven clamp mechanism. In this way, the spare fibre prepared from the package is not damaged in the effort required to physically move the cable. The handling of the fibre package must be carried out carefully, and controlled at the minimum bend radius chosen. The fibre package is placed in the final storage location, sometimes by using guiding tubes, pegs or grooves or some other support to ensure correct placement on the bobbin or tray mechanism within the joint box. It is these internal components that enable storage of up to 2 m of fibre.

It is seen that the ferrule and pressure-tube support collar are the key items to be modified if the overall joint structure is to be adopted to accommodate more than one cable design. Some designs improve electrical conduction between the terminating mechanism and the cable itself by means of a safety pipe consisting of copper or aluminium sections that are friction welded or ultrasonically crimped to the pressure tube and ferrule.

Optical-fibre packages within cable structures generally contain a king wire for the purposes of enabling manufacture. This wire is generally insulated and so is soft soldered or crimped with a small ferrule and re-insulated. For those cables where the king wire forms part of the supervisory system, its insulated continuity is maintained through the joint. Insulation is frequently by means of an epoxy resin, which also provides mechanical locking.

The fibres are generally coloured for identification and so can be cut appropriately into matching pairs. For bobbin storage systems, the splice is arranged to occur centrally but with staggered lengths so that after wrapping they are more or less evenly distributed in the bobbin slots. Fibres are primary and sometimes secondary coated with protective materials immediately after manufacture. Special clamps and mechanical strippers are used to remove one or both coatings to predetermined lengths. The coatings are sometimes softened and swelled by presoaking in different solvents. Alternatively, automatic chemical etching has been used to minimise mechanical stress.

FIBRE CLEAVING AND FUSION

The splice loss is critically dependent upon the cleaving and fusion process. It is probably true to say that these two essential items have been subject to the greatest development effort. There is clear evidence that careful handling, the avoidance of unnecessary touching of the stripped glass fibre and scrupulous cleanliness help to achieve high-strength splices. The low-loss splice depends upon the perfection of the fibre cut, the fibre alignment and splicing conditions. The prepared fibre end is generally clamped on the primary or secondary coating, occasionally both. The bare fibre end to be discarded is lightly clamped and tensioned. The cleaving principle is one of consistently applying a gentle tension onto the fibre surface, which causes minute surface damage, and then controllably propagating this initial crack through the fibre. The stress-raiser device can be either a hot wire lightly touched onto the surface of the glass fibre, to give a thermal stress, or a diamond knife blade of precise mass and velocity, to give a mechanical stress. The fibre surface stress is created by either axial tension or slight bending across a curved anvil. Ideally, a perfectly cut flat surface that is normal to the fibre is required. However, microscopic examination of the fibre end will reveal the site of the stress raiser that causes the propagation of the crack, and this is at an angle of less than 1° from normal, and frequently of 0·5° or approaching 0·25°.

Two fibre splicing methods are used, either arc fusion or flame fusion. They both have their merits and historical development effort, but arc fusion tends to predominate. A multitude of different techniques and fusion machines are now available, but all have perfectly aligned V grooves into which the fibre can be lightly clamped. The clamping may be either to the secondary coating, or to the bare fibre, but generally to the primary coating so that the fibre is not damaged or weakened. One glass block with the V groove and fibre is then moved in 1 μm steps in the X, Y and Z planes with respect to the other. This may be done visually with a microscope with coarse and fine adjusters or automatically with various sensors and stepper motor control to ensure accurate alignment of the fibre ends.

The actual fusion process is automatically controlled by a microcomputer to give an accurate repeatable sequence of events, all optimised for the fibre type to be fused. This sequence can be determined under laboratory conditions and preprogrammed for shipboard use. Once fusion is activated, the fibres are separated from their lightly butted condition symmetrically about the electrodes; the arc is struck, and the fibres overfed symmetrically through the increasing arc. The arc is then reduced in power to anneal the fibre. The process can be viewed by the operator through the illuminated microscope, generally with two orthogonal views. Experienced operators can detect poor splices by this method which can then be cut out. As there is always stored spare fibre, repeat attempts do not pose a problem.

As well as cladding alignment, core alignment can be monitored visually. A further improvement in alignment can be achieved by monitoring the optical transmission power through the fibre core and optimising this during the fusion process. On a ship, transmission power cannot be measured, but for Ge-doped cores, fluorescent emission can be created by ultraviolet light. A computer can readily detect the centre of the core from the light intensity level and thereby adjust the alignment. Techniques are also available for locally launching light into the fibre on one side of the proposed splice and extracting it on the other side. Although the light coupling from local bending of the fibre is poor, it is still possible to optimise the core alignment at the splicing location.

By way of example of the splice loss achieved with arc fusion, by either transmitted power monitoring, or direct core-position monitoring, an average of 0·042 dB for 40 splices with a standard deviation of 0·014 dB has been quoted. An average strength of 3·4 GPa and more than 3% elongation is achieved, which is as high as that for this particular parent fibre.

Flame fusion splicing is characterised by high-strength splices that are equally strong or stronger than the proof test strengths. Fusion splice strengths of 5·5 GPa are achieved through the use of chlorine-hydrogen-oxygen flame fusion. In this method, the thermally accelerated corrosion of the fibre surface, which normally reduces fibre strength, is avoided because of the protection afforded by the chlorine atmosphere, which replaces or substitutes surface OH on the fibre. For those situations where chlorine cannot be used, a modified proprietary oxygen-hydrogen flame fusion process can be used, resulting in splice strengths in excess of 3·4 GPa, which is adequate for most current applications.

INSPECTION

When fibre splicing is done at sea, especially in the instance of a final splice, it is not possible to determine directly the optical transmission loss from the ship or shore ends. This is the predominant reason why fusion machines have a high degree of automation to reduce the dependance of the outcome on the skill level of the jointer. Most of such computer-controlled machines give an estimate of splice loss and, at the very least, a pass/fail criterion. Some designers include a proof test on the final splice, and reinstatement of the original primary or secondary coatings.

A novel technique has been developed to satisfy this particular requirement. After visual inspection during the arc fusion, acceptable splices are transferred and placed into a glass channel by using a transfer jig to avoid straining the splice. When all the spliced fibres have been placed in glass channels, the secondary coating of nylon is bonded to the channel ends with a quick-set epoxy. The central space around the splice is filled with a refractive-index-matching ultraviolet-curing monomer. The splice and channel become an optically transparent block after cure, but, with a high-resolution high-magnification display system, the core-to-cladding and cladding-to-support-tube interfaces are visible. By axial rotation of the block, two orthogonal views are available. By axial scanning, the splice point can be determined and the geometry of the core interface completely evaluated. In this way, a very accurate estimate of the real transmission loss can be obtained on a final splice by comparison with recorded laboratory measurements. Typical losses of better than 0·1 dB can be achieved at 1·3 μm.

FIBRE STORAGE

It is interesting to note how various joint designers have recreated the same environment as in the parent cable. Not only during cable preparation are the oils and jellies not allowed to spill out and degrade the fibre in the cable, but these substances are often reintroduced to completely fill the joint housing. This is important for fluid waterblocking media in order to equalise sea pressure in case of accidental cable severance or damage. For solid waterblocking compounds in the cable, the joint designer does not have such a problem, assuming that the designer has total faith in the efficacy of the waterblocking material. On some systems, the ferrule and bulkhead collar areas are filled with a hard-setting epoxy resin as an additional safeguard against water ingress. Assuming close tolerances on all the piece parts, O-rings and seals where appropriate, a dry air environment is perfectly permissible. Often a desiccant is used to maintain low humidity.

The length of spare fibre stored varies from design to design, as does the number of splices. Some designs have sufficient space for attenuators. The splices themselves may be physically constrained in assigned locations or be left entirely free to take up their own geometry. Some fibre pairs with their splices are stored in the same plane on a flat tray, whereas others are stored circumferentially on a former.

PRESSURE TUBE

All cable joints have a sea-pressure-resistant tube or sleeve as a single or two-part structure. This is slid or screwed over the supporting bulkhead collars. O-ring seals are used to prevent sea-water ingress in case of damage as well as polyethylene ingress during the overmoulding process. Reinstatement of the cable insulation is by moulding with the same grade of polyethylene as the parent cable, either simultaneously at both ends, or sequentially. This process is now frequently automated to produce a repeatable quality product. To reduce the volume of the moulding, most joints have a pre-moulded polyethylene sleeve over the steel pressure tube. For armourless cables, the complete joint is frequently covered with another metal tube, of steel or beryllium copper to provide abrasion resistance and protection. It is to this tube that rubber or polyamide tapered buffers are applied to control the radius of curvature of the cable on handling. This provides a graded transition from the stiff joint to the flexible cable.

Normal practice ensures that the final moulding is examined radiographically. New X-ray cameras have been developed for the large diameter of the joint, so enabling the detection of voids, inclusions or non-homogenous amalgamation zones that could cause high-voltage electrical breakdown of the cable insulation.

ARMOUR REINSTATEMENT

The inner structure of an armoured cable joint is nearly always the same as that for a non-armoured cable. In one solution for an armoured cable, a preformed steel stopper is applied to the armoured cable, over the armourless joint and onto the armoured cable the other side. Although this technique is quick and gives ease of assembly on board ship, it is not an entirely robust solution, as differential elongation can occur between the cable armouring and stopper armouring. This is, in effect, the equivalent of a long overlay splice.

More generally, the armour wires are terminated to an external metallic tube, which ensures mechanical strength with no slack. This tensile structural tube replaces the abrasion protection tube around an armourless joint. The techniques used for terminating the armour wires are various: either individually crimped wires for location in slots, a collectively swaged wire layer around a hardened hollow tube insert or a mechanically-screw-clamped wire layer by means of toothed conical jaws. Torque and rotation are thus effectively transferred from one side of the joint to the other.

Double-armoured cables tend to have one armour layer cut back and only one strength layer transmitted through the joint. If necessary, the beach ends of the cable can be clamped to a concrete block by using the same type of components as in the outer housing of the armoured joint. The shore-end earth seal and terrestrial cable joints have similar arrangements.

TESTING, TOOLING AND TRAINING

The development phase of any joint structure must include a stringent type-approval and quality-assurance programme to make sure that an apparently innocuous detail is not overlooked. This would include tensile tests to the breaking load of the cable with a check on the optical transmission performance. It would be highly undesirable for the fibres to fail prematurely or exhibit increased loss. For a joint possibly in suspension to the bows of a ship, a 24-hour fatigue tension endurance cycle is performed, including peaks and troughs in load to simulate typical mean and significant wave conditions. A linear cable engine module is used in conjunction with horizontally disposed sheaves to simulate the laying and recovery from the bows of a ship and passage around the engine drum. Maximum deep-sea pressure is created in a pressure vessel followed by a high-voltage breakdown test. Accelerated high-voltage life tests are also performed. Long-term loss changes are monitored during temperature cycling tests, humidity ingress tests and bump and vibration tests. Each polyethylene moulding core is checked for good amalgamation by means of a flexural life test.

Besides the new array of piece parts, specialised new equipment is required in the form of cable preparation tools, fibre cleaners, fibre splicing machines and new moulds and moulding machines. The materials used in the construction of some optical cables require the use of toxic and corrosive industrial chemicals in a controlled process. Vibration and the natural environment create a need for additional control equipment for some, to the extent of providing a mobile clean room. Even the former modest jointer's frame is now grossly inadequate for the multiple complex tasks that have to be performed in and around it. It must reduce the effect of vibration, be exceedingly strong and rigid, yet also light so that it can be easily dismantled for storage when not in use. A different applicance is attached to it for each stage of the jointing process.

This array of new equipment spans a broad range of new technologies and places new demands on jointers and their skills. The overall task is long and complex. Just a jointer and mate for a few hours is no longer adequate. Repair times for an armourless optical cable range from 9–18 hours; those of an armoured cable are even longer. Thus it is seen that a team of jointers is now required, perhaps working on each end of the cable and then in shifts as the joint evolves. The range of skills, despite some automated equipment, has to be wider. This places new demands on jointer training, both on suitability and past experience, but also for the specific aptitudes of handling fibre carefully and intelligently. An extensive new training programme is therefore required.

CONCLUSIONS

The development of optical-fibre submarine cable joints has involved a broad range of engineering disciplines. Although development on various aspects will continue, complexity will increase, and this will lead perhaps to more automated equipment. High reliability will thus become of paramount importance. Currently, all joints are specific to a particular cable design, whereas clearly a whole new joint with its associated development and tooling is undesirable as optical cable systems emerge. Some joint constructions lend themselves quite favourably to adaptation to other cable designs. Over a 25-year service life, it is quite likely that new stock cable would be spliced in for repair, thus reinforcing the desirability of developing a universally adaptable joint. The benefit to maintenance operators is clear insofar that only one repair cable, one jointing system and one set of training are all that are required, except for discrete piece parts for the variety of cable structures that will exist.

ACKNOWLEDGEMENT

Acknowledgement is given to the Director of British Telecom Research Laboratories for permission to publish this article.

Biography

Tony Gould graduated from Leeds University in 1972 with a B.Sc. in Mechanical Engineering. That year, he joined British Telecom working on the theoretical aspects of coaxial, and later optical-fibre, submarine cable design. In 1984, he assumed responsibility for all aspects of optical-fibre submarine cable, jointing, terminations and associated technology.

Network Planning: The New Opportunities Created by Submarine Optical-Fibre Systems

J. M. HORNE, C.ENG., M.I.E.R.E., D.M.S.,[†] and K. D. FITCHEW, B.SC., C.ENG., M.I.E.E.[*]

UDC 621.315.28 : 621.391.63

Branching units have already been designed to allow submarine cables to carry separate fibre pairs between different destinations in a common cable structure. Improved flexibility would be available to the network planner if it were possible to use a single fibre pair to carry traffic to different destinations, but this would require a complex branching unit to allow traffic to be combined and split on a time-division basis. This requirement could be met for various fibre configurations by using time-division multiplexing in either continuous or burst-mode time-division multiple-access formats. Feasible solutions exist and some alternatives are outlined in this article; the technical problems are, however, formidable.

This article is based on a paper originally presented at the Suboptic 86 Conference, Versailles, France, Feb. 1986[‡].

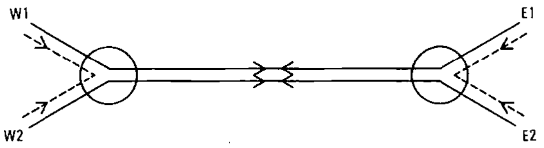
INTRODUCTION

With the modular nature of optical-fibre systems, the high capacities that are potentially available and the possibility of submerged as well as terrestrial branching, planners within British Telecom International (BTI) have begun to consider the alternative networking arrangements that such systems could provide.

This article outlines the network alternatives that have been considered, starting from that to be employed on the TAT-8 transatlantic cable, and reviews the various fibre configurations that could be used within these networks, along with their design constraints.

Complementary to these planning activities, research laboratories have begun to investigate the design and technology requirements needed to implement some of the more sophisticated integrated networks employing complex branching units. The latest work at British Telecom Research Laboratories (BTRL) is outlined.

In conclusion, some of the factors that influence the network decision are discussed.



Note: Capacity between W1 and W2 and between E1 and E2 provided for diversity and restoration purposes only

Fig. 1—Type A network

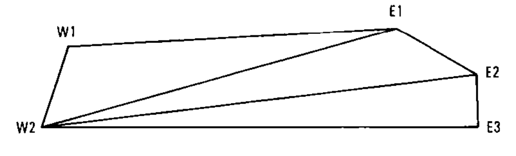


Fig. 2—Type B network

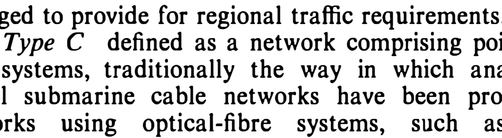


Fig. 3—Type C network

NETWORK ALTERNATIVES

For traffic planning purposes, three theoretical network types have been formulated to consider the network alternatives; these are outlined below:

(*a*) *Type A* defined as a network having a long high-capacity common path and relatively short spurs. A typical network is shown in Fig. 1. Networks of this type are already planned for crossing the Atlantic and Pacific Oceans; that is, TAT-8 and TPC 3.

(*b*) *Type B* defined as a multi-terminal network where a high degree of interspur traffic may be required. A typical example is shown in Fig. 2, and such networks could be envisaged to provide for regional traffic requirements.

(*c*) *Type C* defined as a network comprising point-to-point systems, traditionally the way in which analogue coaxial submarine cable networks have been provided. Networks using optical-fibre systems, such as the UK–Belgium No. 5, Optican and France–Corsica, have been planned in this way; a typical example is shown in Fig. 3.

In reality, a network would be a combination of different types, the Pacific network comprising TPC 3 and HAW 4

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[*] Technology Applications Department, British Telecom Development and Procurement

[‡] HORNE, J. M., and FITCHEW, K. D. Network planning: the new opportunities created by submarine optical fibre systems. Proc. Suboptic 86 Conf., Versailles, France, Feb. 1986, pp. 333–340

being a good example. It is also possible that different types of network could co-exist within the same cable structure and that, where branching is required, as in the Type A and B networks, this could either be undertaken terrestrially or in a submerged branching unit.

TAT-8 with its relatively simple 'Y' branching unit[1] is the first planned commercial application of submerged branching technology within an optical-fibre submarine cable network. The branching unit in this case principally enables the two fibre pairs in the main cable to be split, with one pair terminating in France and the other in the UK, although it also provides static path switching for restoration purposes.

It is possible, however, that a more complex branching unit than that used on TAT-8, enabling a number of lower-capacity users to share a higher-capacity common path, by allowing traffic multiplexing or switching, could have operational or economic merits, providing it was technologically possible.

The following section examines the possible fibre configurations using submerged branching units that could exist within the Type A and B network alternatives and outlines some of their design constraints.

FIBRE CONFIGURATIONS AND DESIGN CONSTRAINTS

Each of the theoretical Type A and B networks outlined above could be provided by using a number of different optical-fibre configurations. These are indicated below and outlined diagrammatically in Fig. 4:

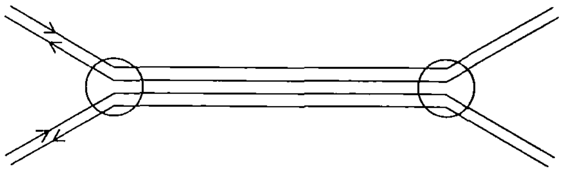
(*a*) direct/indirect-fibre pairs and ring configurations (the latter may use either standard multiplex or packet switching equipment);
(*b*) broadcast; and
(*c*) time-division multiple-access (TDMA) and submerged multiplex configurations with varying degrees of submerged branching unit complexity.

The choice of a particular fibre configuration for a network would be dependent upon a number of factors, some of them operational and others of a political or economic nature. Of principal importance from an operational planning viewpoint are the following: the technology developments required including reliability; the capacity needed including restoration; security of information; security of system operation; constructional flexibility; and operational flexibility. With these factors in mind, the design constraints of the fibre configurations outlined above are now discussed.

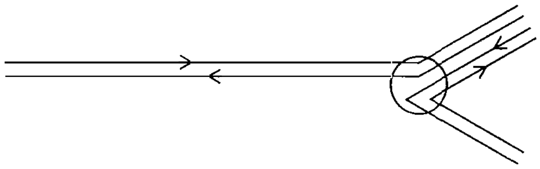
Technology Availability

Currently, the only system technology commercially available is that suitable for use on the direct/indirect pairs, multiplex ring and broadcast fibre network options. Where these require a submerged branching unit, its technology would be similar to that being provided for TAT-8. Whilst the multiplex ring option would use standard terminal multiplex equipment, specialist packet switching terminal equipment would need to be developed for the other ring options.

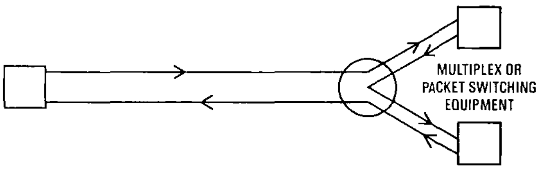
New technology would also have to be developed for the various complex submerged branching units described and could in theory provide considerable network flexibility. These complex branching units would require a high component count and probably have a high power consumption. Their reliability would need to be commensurate with that of the remainder of the submerged plant, and this is one of the prime technical factors of consequence in the implementation of this form of network.



(*i*) Direct-fibre pairs

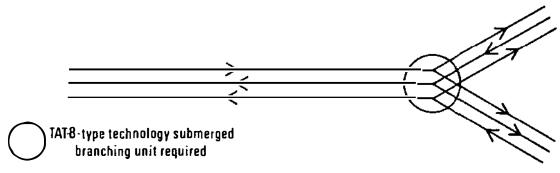


(*ii*) Indirect-fibre pairs

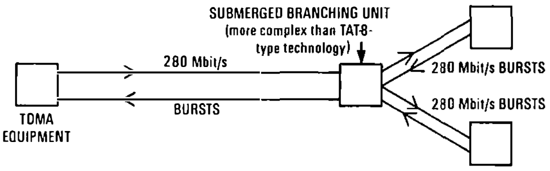


(*iii*) Ring configuration

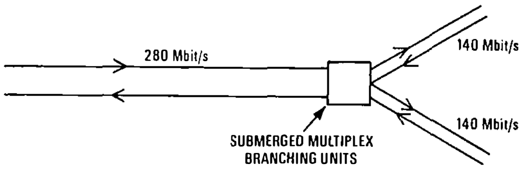
(*a*) Direct, indirect and ring configurations



(*b*) Broadcast



(*i*) TDMA configuration



(*ii*) Submerged multiplex

(*c*) Time-division configurations

Fig. 4—Fibre configurations

Capacity Provided

In general, the direct-fibre pair solution whereby each pair of terminals has a dedicated fibre pair provides the maximum capacity, but at the risk of low fibre fill factors. All the other options provide a more limited capacity determined by the number of terminals sharing a fibre or fibre pair, but with the benefit of higher fill factors.

For restoration flexibility, the provision of additional fibre pairs, static path switching or an increase in fibre pair digital capacity could be considered.

Security of Information

The highest level of information security is provided by the direct-fibre pair solution and those employing active branching units. In these cases, terminals receive only the traffic destined for them. In the other options, the terminals receive all or some of the traffic destined for the other terminals, although it has to be noted that this is general practice for existing networks comprising point-to-point systems.

Security of Operation

Security of operation is a factor of increased importance for complex networks, and procedures have to be such that a cable fault (or its subsequent repair), or misoperation by one terminal, either accidentally or deliberately, does not shut down the whole network. It is possible by good planning of power feeding and supervisory facilities to minimise the risk of this occurring, but all Type A and B networks are inherently more vulnerable to short-term interruptions than Type C networks.

Constructional Flexibility

The ability to extend direct-fibre pair and broadcast configurations is limited, unless spare fibres and regenerators are incorporated in the cable at the time of network construction. There would also be a limit set by the maximum number of fibres that could be accommodated within a cable structure or the number of regenerators that could be housed within a repeater.

For the other options, new spurs could be added, but the traffic capacity available between the original terminals would be reduced. Therefore, it may be necessary to provide additional capacity at the time of construction to retain this flexibility.

With all fibre configurations, it would also not be possible to interface a different technology submarine system to an existing submerged branching unit network unless it had common operational parameters.

Operational Flexibility

The operational flexibility available after the network has been constructed would depend primarily upon the facilities built into the branching unit. Fibre switching to allow traffic to be directed from the main path onto a spur could provide a coarse form of flexibility, whilst a terminal-controlled complex branching unit could provide much greater operational flexibility.

TECHNOLOGY REQUIREMENTS FOR COMPLEX BRANCHING UNITS

Certain of the network options outlined above use branching units of the type to be included in the TAT-8 and TPC 3 cable systems. In networks of this type, each traffic path uses a dedicated fibre pair, although static path switching may be provided to allow the system to be reconfigured as required. The other network options involve the more complex concept of sharing a common fibre path for traffic on different routings, and it is the technical options of networks using these complex branching units that are now considered. This study is restricted to the consideration of systems using binary light-intensity modulation in which path sharing is achieved on a time-division basis. The problem is thus one of combining two traffic paths onto a single fibre pair by using time-division techniques. It is assumed that the traffic building blocks would be in accordance with recommended CCITT† hierarchies, and that transparent channels are to be provided (any use of circuit multiplication techniques is the responsibility of the user of a traffic block).

Sharing of a common path on a time-division basis can be achieved in a number of ways, but these mainly fall into one of two categories:

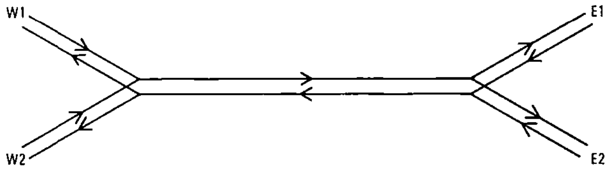
(*a*) interleaving of tributaries on a bit or word basis, or

(*b*) interleaving of much longer packets of data or bursts, as in a satellite TDMA system.

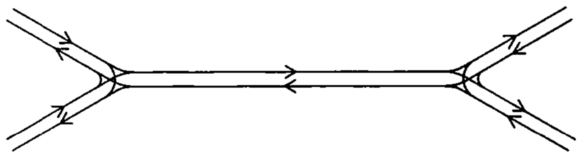
The implications of these two different approaches are considered below, but it would be useful first to review the types of network and the general requirements of complex branching units.

Network Types

From the technology viewpoint, it is useful to classify complex networks in a rather different manner from that relating to the traffic requirements. Fig. 5(*a*) shows a configuration where the Eastward (E) and Westward (W) fibre networks are independent, there being no facility for local traffic between W1 and W2 or between E1 and E2. Fig. 5(*b*) shows a linked-pair network in which the two directions cannot be separated. For most of the technical variants detailed below, the type of submerged hardware required for the linked-pair option is fundamentally the same as that required for the independent fibre option except that more of it is needed in each branching unit. (It is apparent that each branching unit in Fig. 5(*a*) contains two 'nodes', whereas those in Fig. 5(*b*) contain six.) Linked-pair networks offer the possibility of more efficient use of capacity by allowing local interspur traffic to use the same tributary fibres as are used for the main traffic paths; however, if more than one complex branching unit is to be used in any one network, the linked-fibre configuration results in more complex synchronisation problems than the independent fibre type.



(*a*) Independent-fibre network



(*b*) Linked-pair network

Fig. 5—Network types

Summary of Requirements

The design of a data format for a transmission path suitable for time-division operation in complex branching units requires the following factors to be considered.

(*a*) For reliability reasons, the hardware of the branching units must be as simple as possible, preferably using the same technologies as have been qualified for the repeaters. An additional reason for simplicity is the need to limit power dissipation to a level that can be handled in a pressure housing.

(*b*) The system must cater for changes in path delay due, for example, to temperature changes. If a synchronous

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† CCITT—International Telegraph and Telephone Consultative Committee

system is to be used, consideration must be given not just to the means of maintaining synchronisation on the network itself, but also to any justification required in interfacing with the terrestrial networks feeding the tributaries.

(*c*) A supervisory system must be provided for the repeaters of the line system, and for the branching units themselves.

(*d*) In the event of a cable fault or repeater failure, it must be possible for unaffected parts of the network to remain in traffic, possibly allowing the traffic path to be reconfigured to minimise the loss of capacity. In addition, the power feeding and supervisory arrangements must be tolerant of faults.

(*e*) It would be preferable for parameters to be chosen so that repeaters would be suitable for use in both complex integrated networks as well as in point-to-point links. Compatibility with existing standards, for example, TAT-8, may be desirable, though this could be a major design constraint.

TECHNICAL OPTIONS

Submerged Multiplex Units Using Bit or Word Interleaving

Asynchronous Multiplexing

The most obvious option to consider is the implementation of a conventional asynchronous multiplex unit in a technology suitable for use in a branching unit. This approach has the following advantages:

(*a*) there is no need to synchronise the clock rates of the tributaries, since justification is provided,

(*b*) the justification process caters automatically for phase shifts resulting from changes in the delay of the various cable lengths in the network, and

(*c*) standard line plant can be used, and submerged multiplex units can be 'retrofitted' at a later date to existing networks.

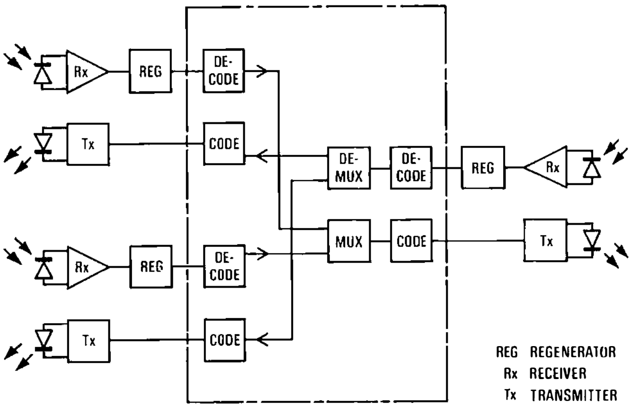


Fig. 6—Branching unit incorporating asynchronous multiplexing on independent-fibre network

However, study of a simplified block diagram (Fig. 6) reveals that the complexity of the circuitry required is far in excess of that provided in regenerators and results in major problems in both reliability and power consumption. The problems become even greater when the requirement for ancillary functions such as supervision is taken into account; consequently, such a system would be difficult to realise with present technology.

Synchronous Multiplexing

A considerable reduction in the complexity of the submerged hardware can be achieved by applying the following techniques:

(*a*) operation of the network in a manner so that the clocks of the various traffic blocks to be combined are synchronous, thus reducing the need for complex justification processes in the submerged plant, and

(*b*) careful choice of the line-code to ease or even eliminate the need for decoding in the branching units.

The complexity required for this type of system depends on the smallest traffic block that is to be manipulated. For the case of combining two 140 Mbit/s tributaries onto a 280 Mbit/s stream the technology may be comparatively simple; suitable choice of line-code may allow a simple bit-interleaving procedure to be adopted. Manipulation of smaller blocks is, however, likely to require significant amounts of storage and parallel processing. In either case, small buffer stores may be required to remove low-frequency jitter prior to combining the data streams.

While synchronous systems are inherently simpler than asynchronous ones, the removal of justification from the submerged plant leaves two aspects to be addressed. First, the clock rates of the building blocks must be synchronised at the terminal stations, requiring both a means of locking the clocks in the various terminal stations and also some form of justification on land. Secondly, a technique must be provided to cater for changes in the delays of the various cable sections (due, for example, to temperature variation). This in fact constitutes a very mild residual requirement for justification. While it may be possible to incorporate this into the repeaters, it may prove necessary to adopt the more complicated approach of using buffer stores at the terminal stations and making use of a telemetry channel from the branching units to signal the requirement for phase adjustments. The latter technique may provide a solution for all cases except that of a linked-pair network employing more than one submerged multiplex unit.

It may be that 2 × or 4 × synchronous multiplex units may be constructed in technology similar to that used for regenerators, though probably requiring a larger degree of integration to achieve a practical solution with adequate reliability. A substantial amount of additional lower-speed circuitry, using a significantly higher level of integration, for both data manipulation and control purposes would be required to provide flexibility at lower hierarchical levels. This is illustrated in Fig. 7, while Fig. 8 shows a hypothetical frame-structure allowing 63 channels of 8·448 Mbit/s to be multiplexed together onto a system having a line rate of 665·28 Mbit/s.

TDMA Systems

Of the various types of TDMA system that can be envisaged, the simplest can be described as a passive burst/idle system. Fig. 9(*a*) illustrates the concept using optical splitters and combiners, although in practice the path splitting might be performed electrically. The main characteristics are:

(*a*) being passive (that is, without switching) only one tributary must transmit data at a time,

(*b*) traffic goes to all distributaries, and

(*c*) because each tributary is idle when not transmitting data, each burst must be preceded by a preamble sufficiently long to allow the successive start-up of the timing circuits of all the regenerators.

Preliminary calculations^2 indicate that the preamble requirement need not be so great as to rule out this approach, but the situation is marginal for a long system.

A more sophisticated variant is the switched TDMA network shown in Fig. 9(*b*); this provides the following advantages:

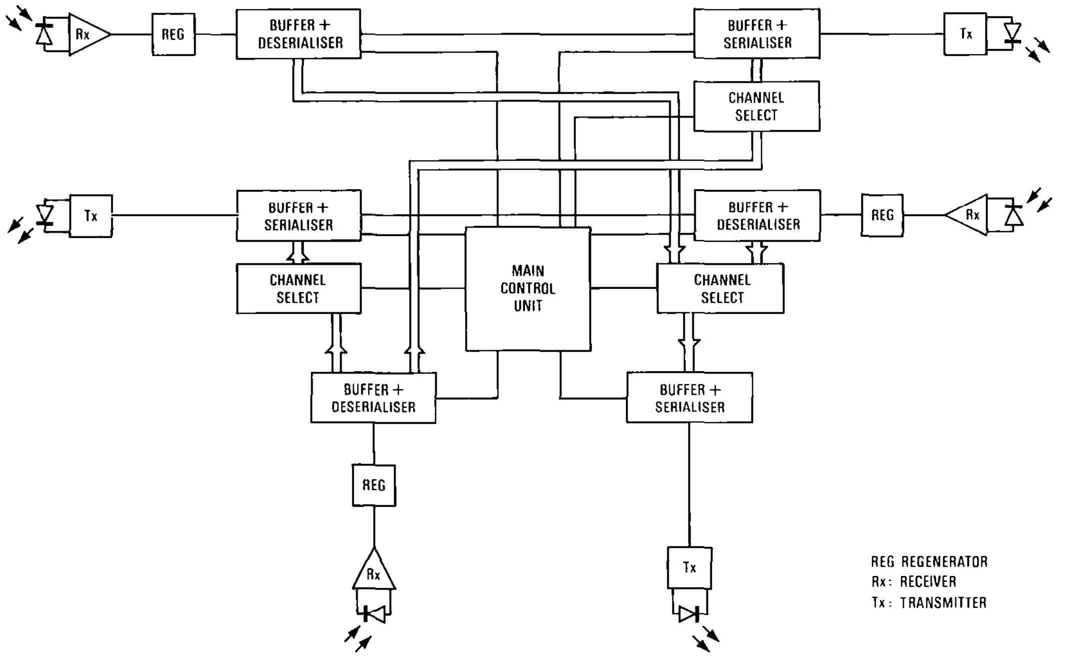
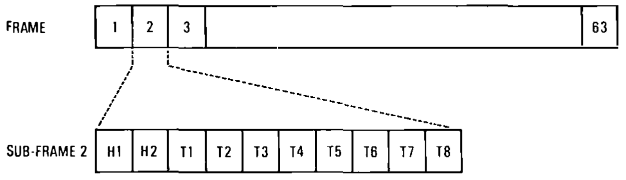


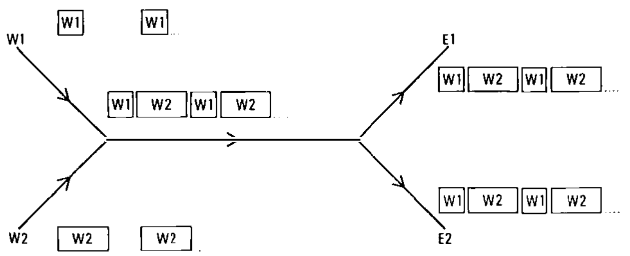
Fig. 7—Data path for synchronous submerged multiplex unit showing complexity for flexibility at 8 Mbit/s



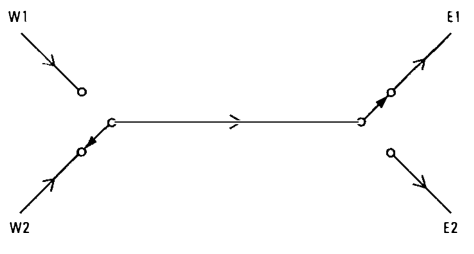
H1, H2 — house-keeping bits provide distributed frame-alignment word, telemetry and parity line coding

T1–T8 — an 8-bit word from the second 8·448 Mbit/s channel

Fig. 8—Simplified frame structure for synchronous multiplexing of 63 channels of 8·448 Mbit/s



(*a*) Interleaving of bursts on passive burst/idle TDMA



(*b*) Switched TDMA system suitable for use on independent-fibre networks

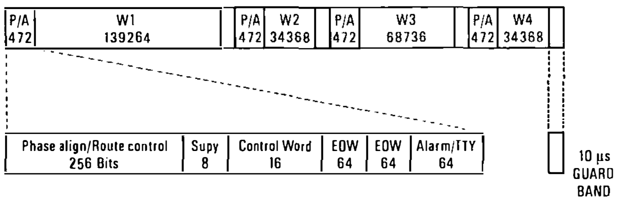
Fig. 9—TDMA networks

(*a*) Since the branching unit accepts data only from the tributary that should be transmitting traffic at any one instant, the other tributaries can continue to transmit a pattern when not carrying traffic. This opens the possibility of retaining the operation of all timing circuits thus greatly reducing the length of the required preamble.

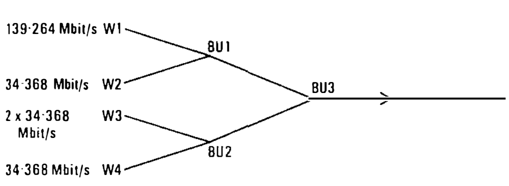
(*b*) Security is improved since only the required destination receives the data.

(*c*) The system is suitable for use in a linked-pair network, although it may prove impossible to form a burst time-plan to allow more than one switched-TDMA branching unit to be incorporated in any one network.

The existence of a guard band between bursts opens the possibility of arranging for it to absorb any necessary bit-slips to cater for changes in path delay, etc. However, circuitry would be required in the branching units to arrange for phase alignment to take place during the preamble of a burst without producing such a phase shift that timing circuits in following regenerators would have to regain alignment. Fig. 10(*a*) shows a possible frame-structure for a complex active branching unit on the hypothetical independent-fibre network shown in Fig. 10(*b*).



(*a*) Possible frame structure for independent-fibre TDMA system



(*b*) Hypothetical network using above frame structure

Fig. 10—Use of complex active branching units

TABLE 1
Features of Networks Using Complex Branching Units

Option	Submerged Plant Complexity	Novel Terminal Requirements	Synchronisation Timing Problems	Operational Difficulty	Flexibility	Compatibility With Existing Systems Designs
Conventional asynchronous multiplex	Very difficult	None	None	Very small	Possible	Yes
Synchronous multiplex	Significant but feasible	Significant	Significant	Small	Possible	Not without major design contraint
TDMA	Quite feasible	Very high	Very significant	Significant	Fully flexible	Impossible

The burst-mode nature of TDMA systems means that it is not possible to incorporate in-service parity bit violation supervisory telemetry techniques without considerable redesign. There should be no problem in providing out-of-service supervision, but there may be constraints on providing in-service supervision over certain parts of the network.

For independent fibre-pair TDMA networks, it may well be that the technology required in the submerged plant may be simpler than that required for similar networks using synchronous multiplex techniques. However, the terminal equipment would be much more complex. The inherent flexibility of TDMA systems in allowing traffic blocks to be redistributed is realisable on independent-fibre pair networks, but can only be achieved on linked-fibre pair networks if they are limited to a single branching unit.

Summary of Technical Options

Table 1 summarises the advantages and disadvantages of the variants studied. Currently, it appears that the synchronous-multiplex option would prove to be the most promising if a satisfactory means of synchronisation can be provided. However, all options represent demanding technical challenges for designers.

THE NETWORK DECISION

The article so far has discussed the new opportunities created by submarine optical-fibre systems from a planning viewpoint and has outlined some of the technology requirements for the more complex active branching units which offer the most economic and operational advantages.

Whilst the optimum network solution has still to be resolved, it is possible to outline some of the important factors that could influence the network decision and these are listed below:

(*a*) The design of a network containing complex active branching units would need to be considered as a whole. The design of each of the line systems included in the network would need to be integrated with that of the branching unit. This would involve both a compromise between the line system parameters and branching unit simplicity, and also agreement on primary line system standards.

(*b*) With an integrated network using complex branching units, either provided in its entirety or in planned stages, the accuracy of traffic forecasting would become more important because of the larger initial investment. A branching unit which had a traffic switching capability would be an advantage in this situation, but it would introduce greater technical complexity and added risk.

(*c*) A method of assigning ownership proportion and hence investment percentage needs to be developed, especially if the capacity of traffic streams could be varied.

ACKNOWLEDGEMENTS

Acknowledgement is made to D. A. Frisch for helpful discussions and C. T. Mallett for provision of technical details of the submerged multiplex options.

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[1] KREBS, G., SKALSKI, J., and SMITH, R. L. TAT-8; System planning and progress. Proc. Suboptic 86 Conf., Versailles, France Feb. 1986, p. 55–61.

[2] ROGERSON, S. P. Private Communication.

Biographies

John Horne joined BT as a Technical Apprentice in 1964. He has been working in the field of submarine cable systems since 1969, and as Head of Systems Engineering Design Group with specific responsibilites for optical submarine cable systems within BTI since 1981. He obtained a Diploma in Management Studies at Middlesex Polytechnic in 1981.

Kenneth Fitchew studied at Bristol University and was awarded a B.Sc. in Electrical Engineering in 1970. He joined BT's Research Department and worked on various aspects of the development of coaxial submarine cable systems. Since 1978, he has worked on the development of optical-fibre submarine systems, assisting in the co-ordination of BT's development work in this area.

Submarine Optical-Fibre Cable Systems: Future Trends

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UDC 621.315.28 : 621.391.63

Submarine optical-fibre systems have already shown notable advancements over systems based on earlier technology, resulting in greatly increased capacity; yet even more significant advances appear feasible. This article reviews the current submarine system technology and goes on to discuss the possible outcome of continuing research into optical-fibre and device technology, forecasting further significant cost reductions, increases in unrepeatered cable lengths and line bit rates by stages until at least the end of the century.

INTRODUCTION

Prior to 1956, cable communication across the Atlantic was restricted to slow-speed telegraph signals. In that year, the first transatlantic telephone system (TAT 1) was opened for service with 36 analogue telephone circuits. Who at that time could possibly have predicted that, just 30 years later, preparations would be in hand to cross the Atlantic with an optical-fibre submarine cable system (TAT-8) having the capacity, enormous by mid-1950s standards, of 7560 × 64 kbit/s digital bearers and, with circuit multiplication techniques, capable of providing the equivalent of 40 000 telephony circuits. (TAT-8 is due to come into service in 1988).

Nevertheless, technological progress is still accelerating and this article reviews the technology currently available and goes on to examine what could become possible over the next decade or so. For the predicted technological possibilities to be realised, it requires direction from and determination on the part of the users, backed up by evidence of customer demand and by favourable results from cost/benefit analyses which need to be performed from time to time as research and development proceed.

CURRENT CAPABILITIES

The UK–Belgium No. 5, TAT-8 and TPC 3/HAW 4 (Japan–USA) systems, together with the simple branching[1] incorporated in the latter two, represent the forefront of current submarine system technology. These systems utilise multiple fibres within the cable, one for each direction of transmission per line system.

They are based upon the 1·3 μm 280 Mbit/s per fibre-pair technology that is rapidly becoming familiar in submarine systems and which is briefly summarised below.

Transmitters

Although a variety of sources exists, that for nearly all fibre systems is some form of semiconductor diode laser. These have the advantage that they are compact low-power devices which can be made both robust and reliable. They give outputs of 10–100 mW and can be modulated by varying the injected current, thereby eliminating the requirement for an external modulator which would be required for most other (non-semiconductor) lasers.

The semiconductor laser is fabricated so that the active layer forms an optical waveguide, with reflective facets at each end providing the feedback necessary to produce the lasing action. The resulting cavity generally supports several modes of oscillation, and the mean output spectrum contains a number of closely spaced lines at differing wavelengths. Given a dispersive fibre, the light from the different modes travels at slightly different speeds, and results in pulse spreading. However, for 1·3 μm systems dispersion is not generally a problem.

The structure of a typical laser proposed for use at 1·3 μm is shown in Fig. 1.

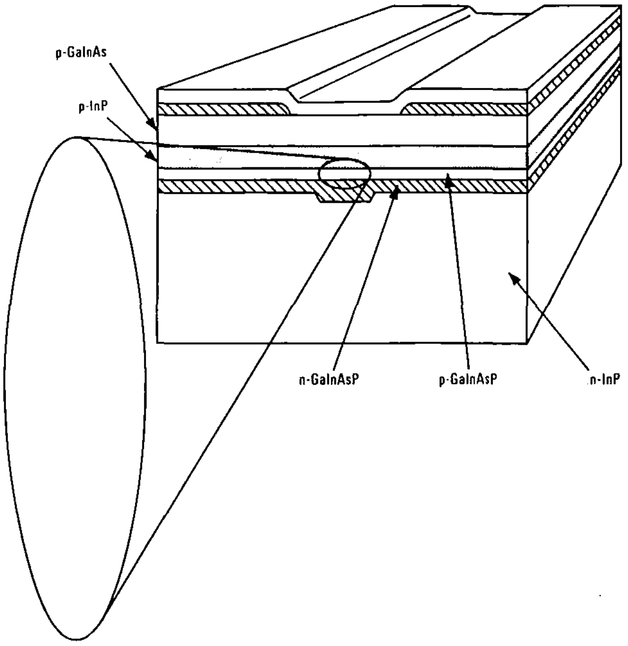

Fig. 1—Inverted rib waveguide laser

Characteristics of Silica Fibre

Fig. 2 shows typical transmission performance of silica single-mode fibre as a function of wavelength. Two low-loss regions are apparent: a loss of about 0·4 dB/km at 1·3 μm and about 0·2 dB/km at 1·55 μm. The lower loss at the longer wavelength is clearly attractive, but the available technology at the time that the design decisions were made for current generation submarine system technology precluded its exploitation.

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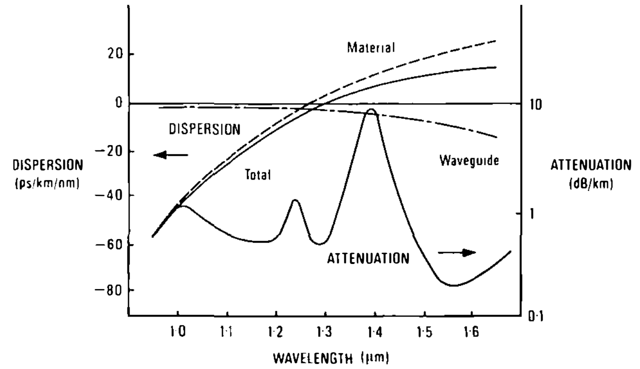

Fig. 2—Attenuation and dispersion of step-index single-mode fibre

Receivers

The receiver consists of a detector photodiode which produces a current in response to light. Either PIN or avalanche photodiodes (APDs) can be used. These must be followed by amplifying circuitry designed for very low noise.

PIN diodes for use in the range 1·2–1·6 μm are made from gallium, indium, arsenic and phosphorus in the form of GaInAs/InP, and are made into small devices to minimise capacitance and leakage currents. The PIN diode generates little noise and the most sensitive PIN-based receivers use a high-impedance PINFET circuit to reduce thermal noise contributions. The use of a high input resistance and a low-noise gallium arsenide (GaAs) field-effect transistor (FET) gives amplification with a very low noise contribution, but the high input resistance combines with the input capacitance to give a large time constant. This produces distortion which requires precise compensation to recover the original signal; it can also limit the dynamic range of the receiver.

In the avalanche device, the photocurrent is multiplied by the avalanche process, with the benefit that less electrical amplification is needed. Unfortunately, leakage currents are also multiplied, and the multiplication process itself generates some noise. APDs can be made from both germanium (Ge) and GaInAsP. Presently available Ge APDs operate well up to 1·53 μm, but exhibit speed limitations at longer wavelengths. There have been encouraging developments of GaInAsP devices with separate absorption and multiplication regions. These devices are just becoming available, and should offer the benefits of an unrestricted wavelength range, an attribute that will be required for future 1·55 μm systems, lower leakage, and less temperature sensitivity.

Receivers based on both PIN and APD diodes give similar sensitivities, but there are significant operational differences. Ge APDs require bias voltages of 30–40 V. GaInAsP devices will probably require 80–100 V, and both will probably need some control to produce the optimum gain.

The PIN diode requires only 7–8 V bias (sufficient to deplete the device) and no control is required. The APD provides some gain, thus reducing the task of the following electronics, and making it easier to achieve good performance. All optical receivers exhibit sensitivities which reduce with increasing line-rate and in general a doubling of line-rate produces a degradation of 3–4·5 dB.

Potential Section Lengths

The maximum section length obtainable is determined by the fibre loss, laser launch power, receiver sensitivity, and desired operating margin. A system with submerged repeaters must be based on highly reliable and well tested components. However, repeaterless systems do not have this restriction to the same degree, and both launch power and receiver sensitivity can be significantly improved. The system parameters shown in Table 1 are for notional 1·3 μm 280 Mbit/s systems, and illustrate both the potential section lengths for repeatered and unrepeatered systems.

TABLE 1
System Parameters 1·3 μm 280 Mbit/s System

	Repeatered	Repeaterless
Capacity	280 Mbit/s	
Cabled fibre loss	0·5 dB/km	
Launch power	−3 dBm	3 dBm
Receiver sensitivity	−33 dBm	−41 dBm
Total section margin	10 dB	
Span	20 dB	34 dB
Distance	40 km	68 km

The figures given for the systems are quite realistic. Launch powers and receiver sensitivities better than the figures quoted above have been achieved at British Telecom Research Laboratories (BTRL). Dispersion should not be a problem at 280 Mbit/s since BTRL transmission experiments at 750 Mbit/s over 65 km of fibre showed no dispersive effects, indicative of a low value of fibre chromatic dispersion.

1989—TRANSMISSION AT 1·55 μm

Unrepeatered submarine systems are not dependent upon the availability of highly reliable components, and therefore will be the first to benefit from 1·55 μm technology. This will probably occur within three years, with repeatered systems, possibly even transatlantic, following perhaps no more than two or three years behind.

By this time, a range of operating rates will possibly be available, including 140, 280 and 565 Mbit/s or thereabouts. TAT-9, when it is provided, will most likely run at the highest rate. Also, as the long-haul versions of 1·55 μm systems become available there may be, as a result of user demand, increased sophistication in underwater branching techniques.

Rather than the simple splitting used in TAT-8, where individual fibres are routed point-to-point, traffic could be directed to different locations by means of underwater multiplexers or time-division multiple-access (TDMA) equipment that will allow interchange of traffic between fibres and hence flexibility in network design.

It is interesting to note that whilst significant technological advances are forseen between TAT-8 and TAT-9 in the optical era, the second transatlantic analogue telephone cable, TAT 2, provided three years after the first. was of essentially the same design.

At 1·55 μm, attenuation is about half that at 1·3 μm, suggesting a doubling of the attainable span, assuming that dispersive effects which limit the distance can be overcome. At 1·55 μm, chromatic dispersion is 15–20 ps/km/nm, compared with 0–4 ps/km/nm at 1·3 μm, as can be seen in the graph showing fibre performance (Fig. 2). Unless dispersion-shifted fibre or a single-wavelength laser is used, the dispersion limits the attainable length.

Production of a laser whose spectrum has been narrowed to a single wavelength can be achieved by a number of techniques, of which one of the most promising involves building a grating into the laser structure to produce a distributed-feedback (DFB) laser[2] (see Fig. 3)

The grating, being wavelength selective, ensures that only one mode of oscillation can be sustained, but there is still some wavelength variation. As the laser is switched on, the changes in current cause small variations, or 'chirp', in the

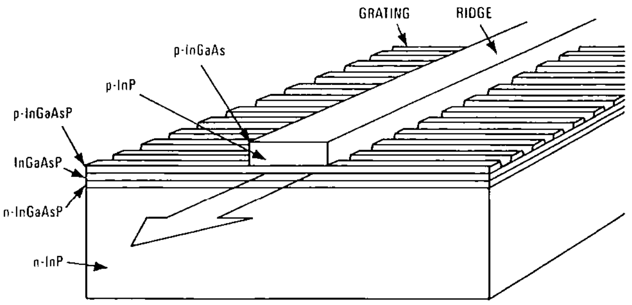

Fig. 3—Distributed feedback (DFB) laser structure

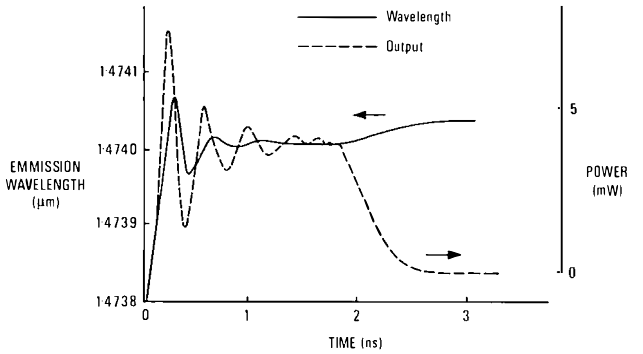

Fig. 4—Intensity and wavelength during DFB laser transient

laser operating wavelength which is shown in Fig. 4.

Alternatively, dispersion-shifted fibre can be produced by changing the fibre parameters, thereby increasing waveguide dispersion which is of the opposite sign to the dispersion caused by material effects, thus producing a fibre with zero chromatic dispersion around 1·55 μm. With conventional fibre and a multi-wavelength laser, the length of a system operating at 1·55 μm and 140 Mbit/s would be limited to 30 km; with dispersion-shifted fibre, the length should be determined by attenuation.

The latest generation of dispersion-shifted fibres achieves both low loss and low dispersion by utilising a roughly triangular index profile. Such fibre has been produced by BTRL and others, and is now commercially available. The source wavelength must be matched to the dispersion zero or there is sufficient residual dispersion to give problems. Also the accuracy of the match becomes more critical for high-line-rate systems, as the pulse broadening becomes a greater fraction of the bit period.

The loss is slightly higher than that of conventional step-index fibre, but there is some evidence that microbending effects (small bends due to mechanical disturbance of the fibre, which can increase fibre losses after cabling) are less, because of the tight guiding inherent in the design. This may make cabling performance at 1·55 μm better than that of step-index designs intended for use at 1·3 μm.

System Experiments at 1·55 μm

In experiments at BTRL during 1984, using components purchased commercially, a 1·55 μm multi-wavelength laser was used to transmit 34 Mbit/s data over 175 km of step-index fibre. Although an operating margin of 5 dB was achieved, the dispersion of the fibre resulted in a penalty of 4–5 dB, and it was clear that longer lengths or higher line-rates would be impracticable.

Two solutions to the dispersion problem were tested at that time. A 140 Mbit/s system using the same 1·55 μm multi-wavelength laser as above was able to transmit over 220 km of dispersion-shifted fibre. An alternative system using a DFB laser to transmit data over conventional step-index fibre achieved a span of 223 km. In both cases the tests demonstrated an absence of dispersive penalties. At higher rates, however, dispersive effects can become apparent with both of these solutions.

Tests at 1 Gbit/s using a DFB laser showed penalties of around 2 dB after 120 km of conventional step-index fibre and other published work shows similar results. The penalty is due to laser spectral 'chirping'.

Use of a normal multi-wavelength laser with dispersion-shifted fibre yielded a span of 107 km at 1·3 Gbit/s, although a close match of laser centre wavelength to fibre dispersion zero was needed to ensure satisfactory operation. This match was so sensitive that temperature variations of a few degrees caused problems. Practical tolerances make a close match difficult to achieve, suggesting that this solution should be limited to systems with lower span line-rate products.

Potential Section Lengths

Returning to lower line rates, it is interesting to examine the possible parameters of a 280 Mbit/s system based on 1·55 μm technology. The performance figures are the same practical values used before and give the expected doubling of attainable span (see Table 2). If in broad terms repeaters are considered to comprise around half the cost of a system, this should give a reduction in cost approaching 25% when compared with a 1·3 μm system.

TABLE 2

System Parameters 1·55 μm 280 Mbit/s System

	Repeatered	Repeaterless
Capacity	280 Mbit/s	
Cabled fibre loss	0·25 dB/km	
Launch power	−3 dBm	3 dBm
Receiver sensitivity	−33 dBm	−41 dBm
Total section margin	10 dB	
Span	20 dB	34 dB
Distance	80 km	136 km

In an attempt to generalise, systems operating at different line rates will be considered. There is no reason why the launch power should change with line-rate, but receiver sensitivity does vary, reducing by 3–4·5 dB every time the line-rate is doubled. Fig. 5 shows the potential spans extrapolated from the calculations above. A range of fibre losses is shown: 0·2–0·3 dB/km for 1·55 μm operation, and 0·4–0·5 dB/km for 1·3 μm.

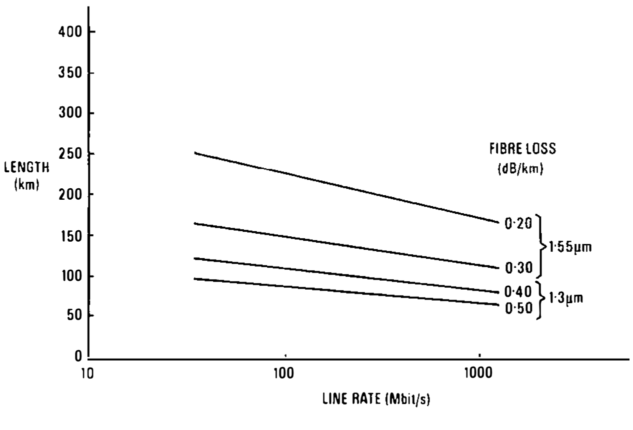

Fig. 5—Practical system limits

The graph assumes that the system length is not limited by dispersion, and assumes the same 10 dB margin for all options, whereas, in reality, each individual system will clearly have its own specific requirements.

A Proposed Repeaterless System

British Telecom foresees its first major exploitation of repeaterless technology as a submarine cable link between the UK and the Channel Islands planned to be in service in 1989. See Fig. 6.

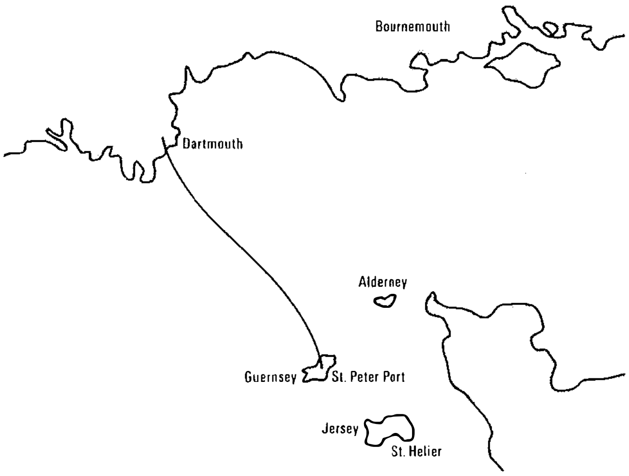

Fig. 6—UK-Channel Islands system route

The system has a section length of about 140 km and will be designed for an initial capacity of 140 Mbit/s/fibre. A span of 140 km at 140 Mbit/s is fairly modest and should permit ample margin for future upgrades, which will require terminal modifications only.

Fundamental limits at 1·55 μm

What then are the limits for a single span? Both launch power and receiver sensitivity are subject to physical limits. In an optical receiver, quantum statistics require a pulse to contain more than 21 photons to ensure that the probability of failing to detect it is less than 10^{-9}. Assuming this figure and a perfect detector (that is, a quantum efficiency of 100%), a 1·55 μm receiver could offer a sensitivity of −66 dBm at 140 Mbit/s. Launch power cannot exceed the Raman scatter[3] limit, which will be about +20 dBm for a typical single-mode fibre at 1·55 μm.

Fig. 7 shows the potential lengths assuming the above ideals; that is, fibre losses of 0·2 dB/km and 10 dB margin. The lowest theoretical loss attainable with silicon fibre is 0·15 dB/km. However, it is unlikely that a cabled fibre will attain this value.

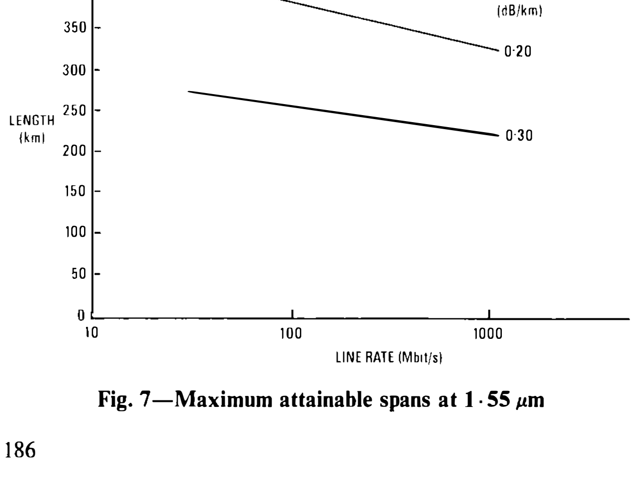

Fig. 7—Maximum attainable spans at 1·55 μm

The limits outlined above are already being approached in laboratories, although it will be some time before fully engineered solutions achieve the same results.

1995—THE TECHNOLOGY BECOMES MORE SOPHISTICATED

Researchers are currently working on a number of advanced optical-fibre technologies, which, when they come to fruition, will mark the emergence of this technology from its equivalent to the 'spark-gap' days of radio. The most promising of these currently appear to be wavelength multiplexing, coherent transmission, optical amplifiers and integrated optics. It is possible that these will begin to find practical use in submarine systems around the mid-1990s.

By this time, the available technology is likely to be able to support 1–2 Gbit/s should traffic demands require it, with increasing use of gallium arsenide technology to produce high-speed integrated circuits. These circuits will in themselves also be more complicated as a result of larger scales of integration so reducing component counts and thereby improving reliability and helping to lower costs.

Again a comparison with the development time-scale of coaxial submarine systems is interesting, where ten years after the first transatlantic telephone system, which utilised valve amplifiers, submarine systems were just beginning to use transistors.

Wavelength Multiplexing

To increase the information capacity by increasing the line-rate encroaches by an additional 3–4·5 dB on the system power budget every time the capacity is doubled. Very high line-rates create practical problems, both with the need for very fast electronics, and rapidly increasing penalties due to dispersive effects.

The use of wavelength division multiplex (WDM) techniques, where several low-rate channels are transmitted at different wavelengths, offers a potential solution to this problem. In a WDM system there will be an inevitable loss of power in the optics used to separate (and combine) the different wavelengths, but this loss should not increase rapidly with the number of wavelengths. Thus, ten channels could theoretically be accommodated for a penalty of only a few decibels, compared with at least 10 dB for a tenfold increase in line-rate. The number of channels is not unlimited, because cross-talk and the losses of the combining/splitting optics become significant for more than a few channels.

Coherent Transmission

Another potentially useful technique is that of coherent transmission. The use of a very coherent optical signal combined with heterodyne and homodyne receivers (similar in operation to radio-reception equivalents) reduces receiver noise, thus giving an improvement in sensitivity of 5–10 dB. It also makes it possible to separate closely-spaced WDM channels. Coherent systems are necessarily more complex than direct detection schemes, but for a repeaterless system this is less of a problem and may offer a useful upgrade path.

Optical Amplifiers

The repeaters for an optical transmission system are currently very complicated, employing both electro-optic and electronic devices. Experimental work has already shown that it may be possible in the future to reduce this complication simply by using the laser itself in a manner not unlike a travelling-wave amplifier. The laser is brought almost to the verge of lasing, so that when received light is introduced into one end of the cavity it is sufficient to cause lasing action, and an amplified pulse can be extracted from the other end and launched into the fibre for onward transmission. At BTRL, such devices have already been producing useful amplification in the order of 20 dB at 1·5 μm.

Such amplifiers would bring with them many other potential advantages including:

(*a*) their ability to be bi-directional,

(*b*) the fact that they can amplify at several frequencies at once and therefore be transparent to WDM, and

(*c*) the fact that systems including only optical amplifiers could readily be changed to operate at different bit rates.

Integrated Optics

Another way of reducing the number of components in a repeater is to fabricate the electronics and the optics from the same material and integrate them, thereby producing robust, compact modules as well as improving reliability and reducing costs. Research work on these techniques is at a very early stage, but may begin to bear fruit within the same time-scale.

THE YEAR 2000—THE DREAM APPROACHES REALITY

It has long been the dream of submarine system engineers that one day it will be possible to cross the Atlantic with a telephone cable without repeaters, just like the early telegraph cables. It may be that optical fibres will provide the nearest approach to this ideal.

At new and longer wavelengths than those currently envisaged, fibres using materials other than silica have very much lower losses, and a number of materials, in particular zirconium tetrafluoride (theoretically 0·01 dB/km at 2·5 μm) and beryllium fluoride (theoretically 0·005 dB/km at 2·1 μm) are being investigated. Practical results have not yet bettered 1 dB/km. The material is much less robust than silica, suggesting a silica outer cladding may be required, particularly since the material has an affinity for water. Nevertheless, by using the better of the above figures and making estimates with similar parameters to those used before (except for the receiver where it has been recognised that it is much more difficult to produce good performance diodes at the longer wavelength) some startling results are produced:

Fibre loss, say	0·005 dB/km
Cabling loss, say	0·005 dB/km
Splicing loss, say	0·003 dB/km
Total loss	0·013 dB/km

This is around 80 km per dB

Launch power, say	3 dBm
Receiver sensitivity, say	−35 dBm
Range	38 dB
Less margin, say	10 dB
Useful range	28 dB

A distance of 2240 km

Should these sorts of numbers become realisable, or even only half as good as suggested, then although it would not be possible to cross the Atlantic without a small number of repeaters, all the European countries currently linked to the UK by cable, including the Iberian Peninsula, would certainly be within unrepeatered range at gigabit/second line rates. All this could, perhaps, be achieved within 14 years from now. (For comparison, it may be recalled that in 1970, only 14 years after TAT 1 went into service, transatlantic coaxial systems were still only carrying relatively small quantities of traffic, and TAT 5 with a capacity of 845 telephone circuits was being provided.)

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Biography

Phil Ranner worked for Pye Telecommunications as a student engineer whilst he obtained his B.Sc. degree in Electrical and Electronic Engineering. He joined BT in 1973 and was assigned to the Submarine Systems Division where he remained, gaining experience on a variety of duties, before taking up his current position. He is now Head of Section responsible for technical standards and development of new submarine systems and transmission equipment in the Satellite and Lines Executive of BTI.

John Horne joined BT as a Technical Apprentice in 1964. He has been working in the field of submarine cable systems since 1969, and as Head of Systems Engineering Design Group with specific responsibilites for optical submarine cable systems within BTI since 1981. He obtained a Diploma in Management Studies at Middlesex Polytechnic in 1981.

Tony Frisch joined BTRL in 1975 after graduating with a B.Sc. in Physics, and worked in a group studying submarine coaxial cable ageing. He moved to work with optical transmission systems and studied part-time for an M.Sc. in Telecommunications Systems. Later work included transmission system tests and studies of the behaviour of lasers. He is currently Head of Group studying future optical systems.

Optical Materials Section at BTRL Wins Queen's Award for Technological Achievement

INTRODUCTION

The Optical Materials and Low Loss Fibre Section at British Telecom Research Laboratories (BTRL), Martlesham, has established a world-wide reputation for its contribution towards the design and development of single-mode optical fibres. Single-mode fibres offer the lowest loss (longest transmission distance) and lowest dispersion (highest bandwidth) achievable in optical waveguides. This type of fibre (see Fig. 1(*a*)) was first proposed in the mid-1960s, but at that time the technology was in its infancy and fibres with very low losses could not be produced[1]. World attention therefore turned to multimode fibre, which was thought to be easier to manufacture and easier to splice with low loss, and good performance was being achieved by the late-1970s[2]. At that time, all planned installations of optical systems involved using graded-index multimode fibres (Fig. 1(*b*)). A major requirement in these fibres is for high bandwidth. In a multimode graded-index fibre, the bandwidth is a direct function of the shape of the refractive-index profile, and, in practice, it was found to be difficult to control the parabolic profile to within the very fine limits necessary to guarantee a bandwidth of, say, greater than 1 GHz km. This meant that repeater spacings of less than about 10 km had to be used for a 140 Mbit/s system, and consequently long-distance systems would need many buried or submerged repeaters. For comparison, the bandwidth of a single-mode fibre at its zero-dispersion wavelength can be greater than 100 GHz km (depending on the characteristics of the laser source)[3].

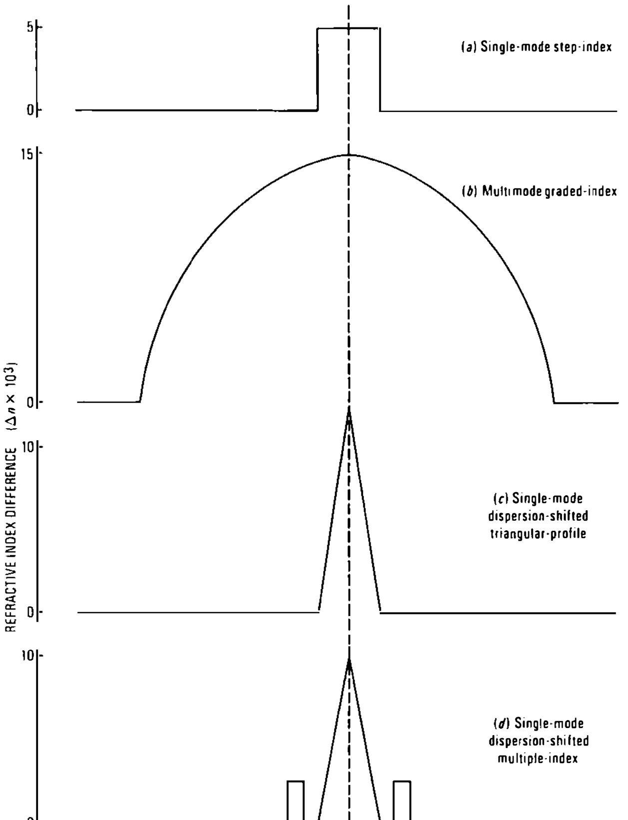

Fig. 1—Refractive-index profiles of optical fibres

In the late-1970s, attention was focused again on single-mode fibres because of their potential attractiveness in undersea systems, where they offered potential repeater spacings of greater than 30 km. This feature also proved attractive for trunk inland systems as it eliminated the need for remote repeaters, and thus gave significant savings (amounting to tens of millions of pounds in the current decade) on both the installation and maintenance costs.

SINGLE-MODE FIBRE DEVELOPMENT

The Materials and Optical Systems Divisions at Martlesham were among the first to recognise the new potential of single-mode fibres and, between 1978 and 1980, the Optical Materials and Low Loss Fibre Section made significant progress in designing and producing single-mode fibres which showed a substantial improvement in performance over the earlier multimode design[4–6]. A key feature of single-mode fibre is its small core diameter (5–9 μm) compared with about 50 μm for the multimode fibres. This led to significant differences in the technology, calling for greater emphasis on controlling the design parameters (refractive index, dimensions, purity). Because most of the light which is guided in the fibre is concentrated in such a small core, the chemical purity of the glass (which affects the loss) is critical. The compositions of the glasses are very important in determining both the optical performance and the productivity and yield in the fibre fabrication process. In the course of this work, the Optical Materials team addressed and solved many of the problems particular to designing and making single-mode fibres.

The fabrication process was developed from the earlier multimode technique of depositing a number of layers of doped silica glass on the inside wall of a silica tube[7]. The glass is generated by reacting silicon tetrachloride and other halides with oxygen in the heated tube. The composition of the glass in each layer is controlled so that material is built up to give the refractive-index profile necessary for a single-mode fibre. The tube is then collapsed to form a solid preform rod which is converted into fibre in a separate fibre-drawing tower. The first breakthrough at Martlesham was the formulation of a (phosphorus + fluorine) doped cladding glass which enabled several problems in preform and fibre fabrication to be overcome and allowed large preforms to be made with good yield. This was followed by a tenfold reduction in the level of hydroxyl impurity in the glass by using chlorine in the collapse stage of preform fabrication; thus, the problem of excess loss at the proposed operating wavelength of 1·3 μm due to this impurity was solved.

Subsequent advances included grading the composition of the cladding glass adjacent to the core to achieve further improvements in optical performance, identifying and controlling a drawing-induced loss mechanism related to the glass composition and drawing conditions[8, 9], and developing gas-phase etching using fluorine during the collapse of the substrate tube to allow fine control of the central region of the refractive-index profile[10].

A range of designs of single-mode fibres was generated for evaluation by the systems design groups. These included fibres with depressed refractive indices in the cladding, and fibres with the wavelength of zero dispersion shifted to 1·55 μm to coincide with the minimum in loss. Collaboration between the Materials and Systems Divisions established that the geometrical tolerances necessary for low-loss splicing of single-mode fibres in the field (without power feed from the terminal) could be achieved in small-scale production at Martlesham, and that the fibre designs which were established were not unduly sensitive to bending losses when the fibres were packaged and cabled. By 1982, the design of the first-generation single-mode fibre had been optimised, taking into account loss, dispersion, sensitivity to bending loss and spot size for splicing, primarily at 1·3 μm but keeping the options open for subsequent upgrade at 1·55 μm (BTRL type 'B' fibre).

Later work focused on optimising the fibre designs for use in the 1·55 μm transmission window and resulted in the development of the world's first dispersion-shifted fibre with ultra-low loss[11, 12]. This single-mode fibre featured a core region with a triangular refractive-index profile (Fig. 1(*c*)) giving zero dispersion and a minimum loss of 0·22 dB/km at 1·55 μm. Improvements in this design led to a 'multiple index fibre' (Fig. 1(*d*)) which retained the excellent loss and dispersion characteristics but included a higher resistance to bending losses and an optimised spot size for splicing[13].

COMMERCIAL EXPOITATION

By developing the fibres through the research phase to a demonstration of laboratory-scale production, the Martlesham team was able to transfer the technology to larger manufacturing plants. The Optical Materials Section licensed the technology for making single-mode fibres to two companies, GEC Optical Fibres and L. M. Ericsson, in 1982, and both now have large-scale production facilities which have provided income in the form of licence fees and royalties to British Telecom (BT), and a competitive manufacturing environment in the UK. The competition between manufacturers has been of particular benefit to BT as it has helped to create an environment in which the cost of single-mode fibre in the UK fell by an order of magnitude between 1982 and 1985. The first-generation type 'B' design has become the UK standard for single-mode fibre and has been used in all of the BT single-mode cable installations to date.

The Optical Materials Section has been able to provide hundreds of kilometres of state-of-the-art fibre to other groups within BTRL and in other parts of BT before this type of fibre was available from any other source. This enabled colleagues in BTRL to develop and demonstrate advanced optical systems ahead of the world, such as the first 100 km 140 Mbit/s systems in 1982[14,15], and, more recently, even longer direct-detection and coherent systems[16,17]. Apart from the reduced installation and maintenance costs mentioned earlier, a further advantage of single-mode fibres is that systems can be upgraded by working initially at 1·3 μm, and subsequently in the second transmission window at 1·55 μm, with the ability to wavelength-multiplex hundreds of channels.

The first transatlantic optical cable, TAT-8, which is due to enter service in 1988, and which is being installed jointly by BT, AT&T and the French PTT, and the first cross-channel optical cable (UK–Belgium), which is currently being installed, both use fibre based on the type 'B' design, operating at 1·3 μm, with repeater spacings of about 40 km. Future systems will operate at 1·55 μm, with possibly repeater spacings of more than 100 km.

QUEEN'S AWARD

The Queen's Award for Technological Achievement, which was announced in April 1985, recognises not only the technological advances made at BTRL in designing single-mode fibres and developing the process technology, but also the successful commercial exploitation of these research results. The award was formally presented to the Optical Materials team by Sir Joshua Rowley, Lord Lieutenant of Suffolk, in September 1985.

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Notes and Comments

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Many IBTE Members and other employees of British Telecom and the Post Office who subscribe to the Journal by deductions from pay have still not yet supplied their home address to the IBTE Administration Office so that copies of the *Journal* can be sent direct to their homes. Back issues of the *Journal* since October 1985, when this new method of distribution was started, are being held in store for these Members and readers until this information is received. Members and readers are asked to remind their colleagues to supply this information as soon as possible if they have not already done so; a form for this purpose was included with the April 1985 issue of the *Journal*. These Members and readers will then be sent the back issues and all future issues to their home address. Any enquires about this notice should be directed to The IBTE Administration Manager, Room 107 Intel House, 24 Southwark Bridge Road, London SE1 9HJ.

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Contributions of articles to *British Telecommunications Engineering* are always welcome. Anyone who feels that he or she could contribute an article (either short or long) of technical, managerial or general interest to engineers in British Telecom and the Post Office is invited to contact the Managing Editor at the address given below. The editors will always be pleased to give advice and try to arrange for help with the preparation of an article if needed.

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The Editors would like to hear from anyone who feels that they could contribute further papers in the series of educational papers published in the *Supplement* (for example, see the paper entitled *Digital Multiplexing*, included with the April 1986 issue of the *Supplement*). Papers could be revisions of British Telecom's series of *Educational Pamphlets* or, indeed, they could be completely new papers. It is intended that they would deal with telecommunications-related topics at a more basic level than would normally be covered by articles in the *Journal*. They would deal with, for example, established systems and technologies, and would therefore be of particular interest to those who are new to the telecommunications field, and would be useful for revision and reference and for finding out about new topics.

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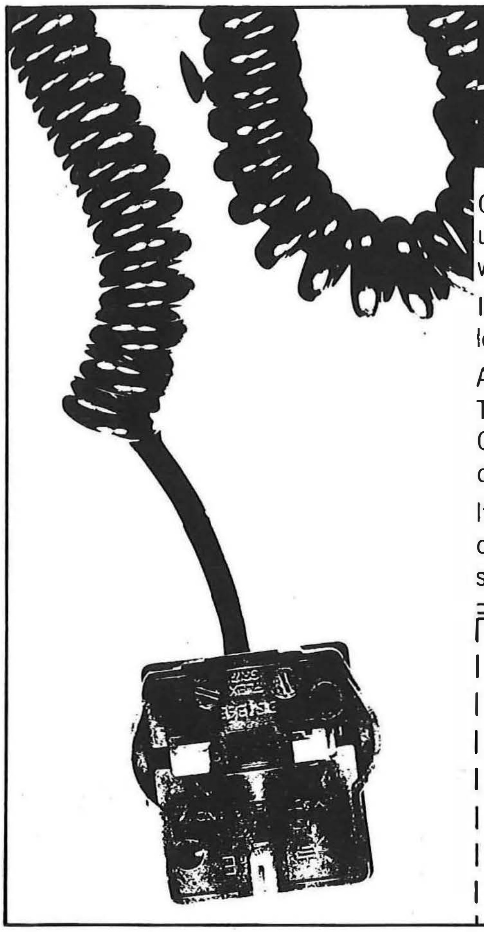

MAJOR NEW TITLES

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TeMart

Mechanical and Environmental Test Facilities at British Telecom Research Laboratories

British
TELECOM

A large percentage of international communications are routed through submarine cables. To ensure an efficient and reliable service, great care is taken in the design and testing of the cable prior to installation.

Technology Applications Department (TA5) have over thirty years experience in evaluating the mechanical, electrical, and, more recently, the optical properties of cable for oceanic systems. During this period an advanced mechanical test house facility has been developed, complete with an experienced and dedicated staff.

TA5 is able to offer these test facilities on a commercial basis to industry.

It can offer a complete test service tailored to specific customer needs.

One or more of these test facilities have been used by most cable administrations and operators worldwide.

PRESSURE VESSELS

The vessels are used to subject various components to external and internal hydraulic pressure.
The pressurisation medium is inhibited water, however other liquid mediums may be used if the sample is bagged (brine or dye penetrant).
Destructive collapse of specimens is possible, provided the collapse volume is limited.

Vessels 1 to 5 are single ended, 6, 7 and 8 are double ended. All have gland ports for external monitoring of the item under test. Electrical, mechanical or hydraulic monitoring of the component is possible. The equipment is designed and maintained to BS 5500, and is subjected to regular inspections. The glanding enables testing to BS 5430.

TENSILE TEST EQUIPMENT

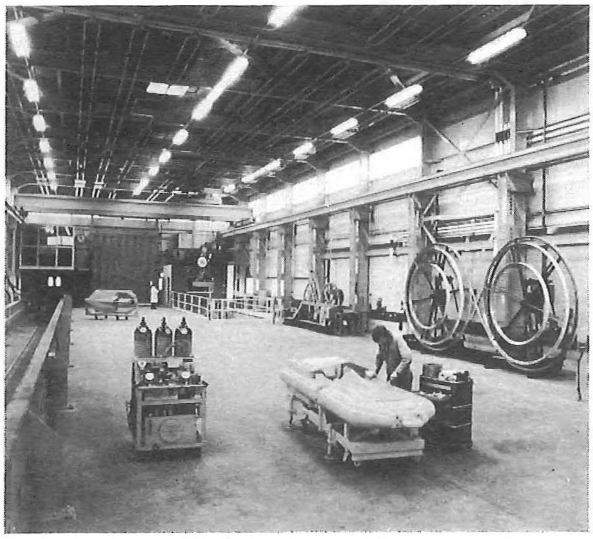
Tensile test machines are used to proof-load and fatigue cables, ropes, chains, cable terminations and joint housings.

Two main tensile machines are available:
Machine 1 1MN (100 ton force)
Machine 2 300kN (30 ton force)
An outstanding feature is their dynamic response capability. Both machines are hydraulically operated and may be used in two modes:

STATIC TESTS (tensile)
DYNAMIC TESTS (fatigue)
For STATIC tests, loadings may be applied and/or decreased using Continuous ramp or Step mode.
Applied loadings can be held for any time period.

For DYNAMIC tests, various wave-forms are available:
sinusoidal sawtooth and square wave or a prerecorded service condition (if within the range of the machine).
Two modes of control are available using either load or ram position.

It is possible under some circumstances to increase the loadings for machine 1 by agreement.
The fastest practical cycling rate is 5 seconds (up to 1HZ is possible on stiff samples).
Various swivels, load cells, torque, displacement and rotation transducers are available.
These are regularly calibrated against approved standards.
Electrical outputs from the measuring equipment are stored in a data-logger and are also recorded on a multi-channel chart recorder.



HIGH VOLTAGE TEST LABORATORY

Oceanic telephone cables operate at high voltages and in order to perform quality control tests, and life prediction tests very high voltages are required.

Two main test sets are available:
a. DC test 0 – 500kV at 100µA
b. AC test 0 – 100kV peak (2kVA transformer with 5A input trip)

A circular water bath of 3300mm (11ft) diameter is available enabling long specimens to be tested immersed in water.
Cable life testing tanks operating up to 40kV DC are also available.
Calibration accuracy is to BS 923 part 3 (1980) and I.E.C. 60 – 2 (1973).

RADIOGRAPHIC FACILITY

Two main X-Ray machines (Balteau) are available at BTRL:
a. Dual focus. Tube potential 400kV max. Tube current 10mA/3mA.
b. Tube potential 100kV max. Tube current 5mA.

Radiographs (X-Rays) are used extensively in the quality control, which includes testing, of aspects of submarine cable work.
These machines enable a wide range of items to be X-Rayed, from thin sections (including integrated circuits) up to steel castings of 100mm section.

There are also available portable BT X-Ray cameras (BT Mk. 9 20kV) for radiographing cables or other low density objects up to 50mm diameter.
All X-Ray units are operated by qualified personnel.
The facilities are supported by a fully equipped darkroom.

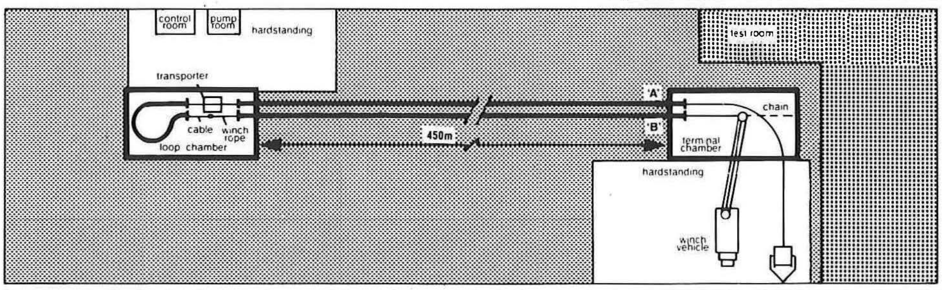
ENVIRONMENTAL TEMPERATURE CHAMBER

The chamber is used for temperature dependant tests on large items of equipment such as cables stored on drums.
A hover transporter may be used to load heavy items of equipment into the chamber.

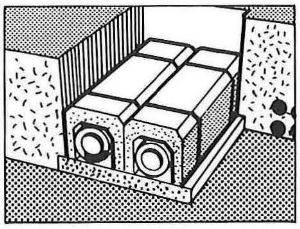
Specification

Temperature range	– 20 to + 60 degrees C.
Temperature stability	+ / – 0.5 degrees C.
Temperature change	1 degree C per hour.
Entrance door size	2.9m square.
Chamber size	3m wide 4m deep 3m high.
Max. weight (on loader)	10 tonnes.

THE OCEAN SIMULATOR



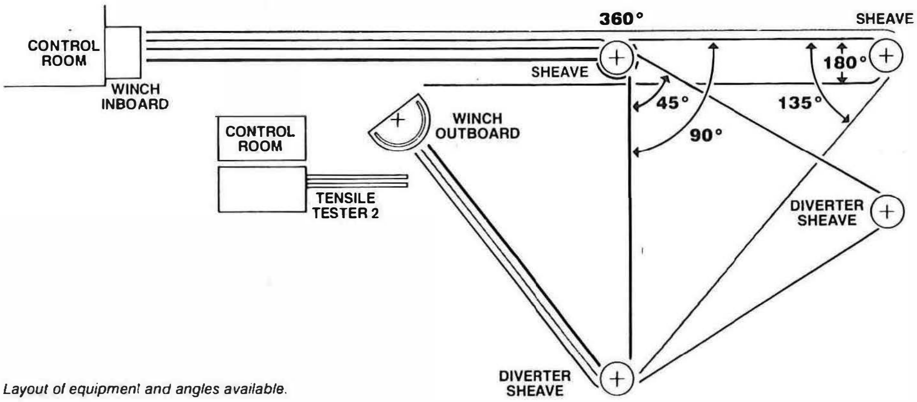
A requirement of any deep water, long haul submarine telephone system, is the prediction of its transmission performance, including any possible ageing effects. The simulator is a unique facility designed to measure any such cable changes, including liquid ingress or gas permeation rates. The Ocean Simulator is a 926m long, temperature controlled, pressure vessel designed to simulate the above environments. It allows various transmission parameters to be monitored, thereby reducing the need for expensive sea trials.
The simulator consists of two straight 450m lengths of pressure tubing. These are each housed concentrically in a thermally insulated casing, containing temperature controlled water. Each end of the pressure tubing is terminated with a GRAY TOOL Co hub. At one end of the simulator the high pressure tubing is coupled by a demountable high pressure "U" bend. The other end of the simulator allows connection of monitoring equipment to the test sample.



"U" bend removed, with cabling transporter fitted.

Other options are available
a. A second "U" bend may be fitted to the simulator complete with cabling branches, effectively doubling the length of the test sample (only suitable for cables up to 40mm in diameter).
b. The main "U" bend may be removed allowing both legs of the simulator to be operated independently.

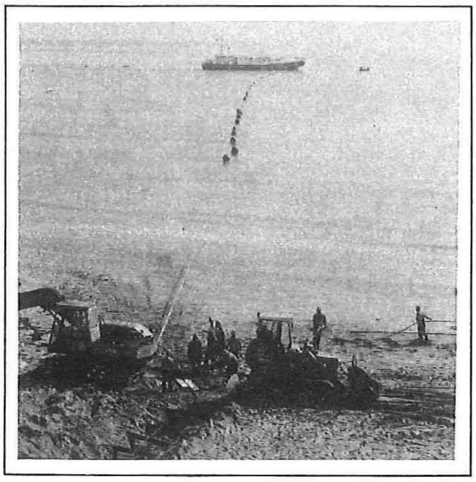
'ROUND THE SHEAVE' FACILITY



Layout of equipment and angles available.

The equipment is designed to simulate shipboard laying and recovery conditions. Cables, repeaters, joints and fittings may be pulled under tension around horizontal sheaves.
The equipment comprises various sheaves and two hydraulically operated winches. The specimen is pulled under load around the sheave by one of the winches, the other acting as a brake maintaining constant back tension.
The specimen may be cycled between the winches. A sinusoidal or other waveform may be superimposed on the basic tensile loading.
The equipment can also be used to provide a "figure of eight" reverse bend test with the sample under tension.

Information or enquiries please contact:
Chris Desbrow: 0473 646954
Tony Gould: 0473 646903



LAYING A SUBMARINE CABLE TWO MILES DEEP IS NO JOB FOR AMATEURS

British Telecom International and its predecessors, have been involved with the provision of underseas cables since the first submarine cable link between England and France, provided in 1851. Since then BTI has participated in more than 100 submarine cables worldwide.

Laying a telecommunications cable in the depths of the ocean demands a high level of expertise employing the latest available technology. There is no room for error – only the best succeed.

British Telecom International is able to supply the total package, from concept to completion, for digital or analogue, coaxial or optical fibre submarine cable systems. Or BTI can assist your project in any single aspect, for example --

NETWORK STRATEGY
DETAILED PLANNING
PROJECT IMPLEMENTATION
SYSTEM MAINTENANCE AND SERVICE ANALYSIS.
TRAINING

Our consultancy services embrace the entire field of underseas telecommunications technology and are available to any telecommunications administration considering provision of underseas cable systems.

In the economic climate of today, where budgets are subject to stringent scrutiny at all levels of business activity, the highest standards of management are essential. Particularly in an enterprise as demanding as underseas communications.

As a world authority at the forefront of this field, British Telecom International also has the additional resources of the British Telecom group of businesses, such as the Marine Services Division, BT's renowned Research Laboratories, and a Procurement Department using the latest philosophies of quality assurance.

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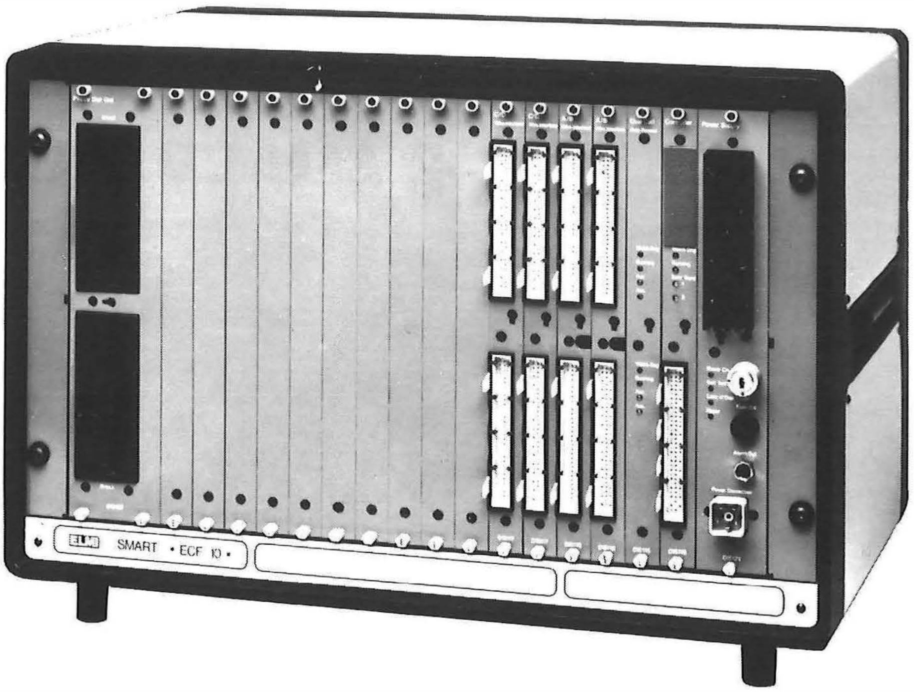

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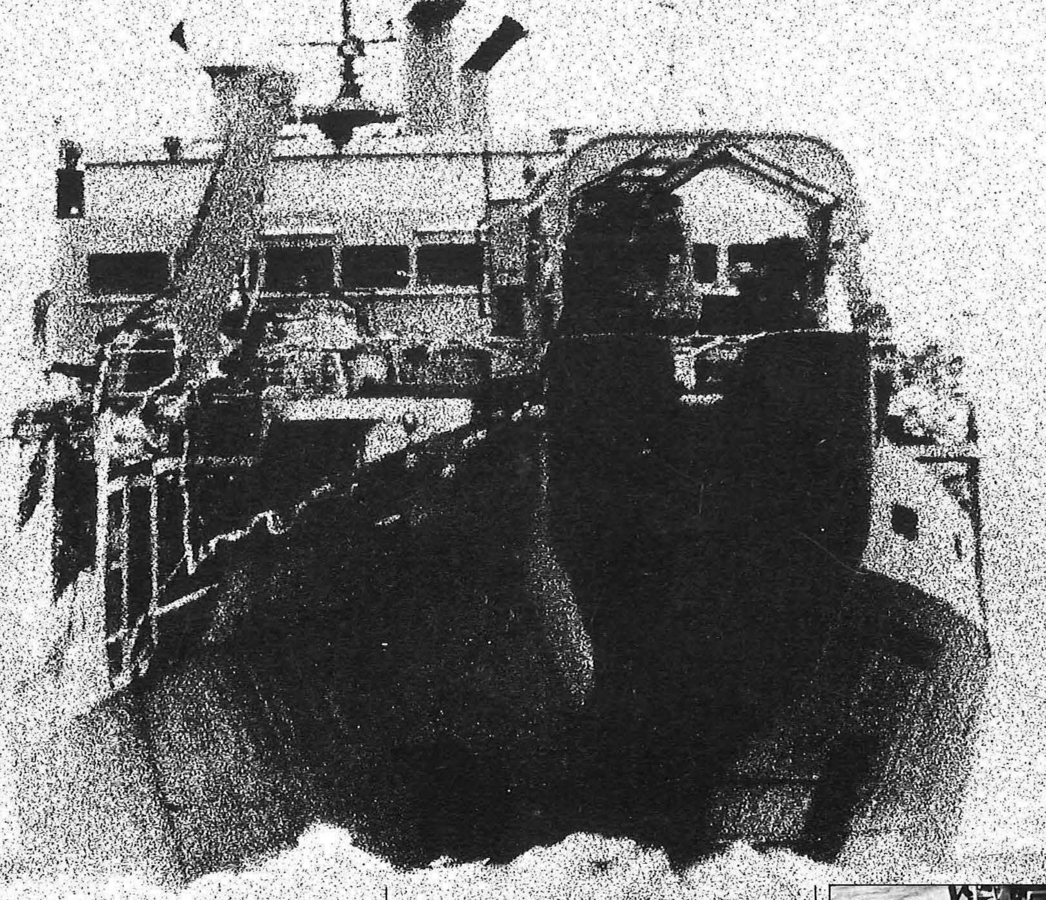

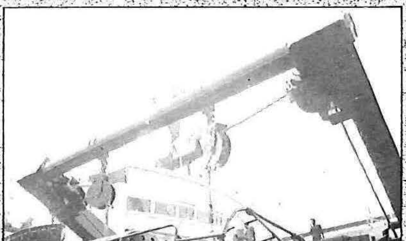
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