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PART A

Part. A.

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PART A

Chancellor's (Lawson) Papers:

ADVISORY COUNCIL ON SCIENCE AND TECHNOLOGY REPORT ON OPTOELECTRONICS

PO -CH /NL/0259
PART A

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From the Private Secretary

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2 March 1988

ACOST REPORT ON OPTOELECTRONICS

The Prime Minister has now received a letter from Sir Francis Tombs proposing publication of this report, as forecast in Vivian Brown's letter to me of 29 February.

I should be grateful for views from the Department of Trade and Industry, and from the other departments to whom I am copying this letter, on whether the Prime Minister should accede to the request for publication. It would be helpful to have comments by Thursday 10 March.

I should also be grateful it you could co-ordinate the drafting of a Government response to the report. It would be helpful to have this by Friday 18 March.

I am sending copies of this letter to the Private Secretaries to the Secretaries of State for Education and Science, Defence, the Chancellor of Duchy of Lancaster and to Trevor Woolley, John Fairclough and Richard Wilson at the Cabinet Office. I am also sending a copy of this letter and the earlier papers to Alex Allan in the Treasury, who may wish to be involved in the preparation of the Government response.

personally, I take it?

M

PAUL GRAY

Miss Alison Brimelow,
Department of Trade and Industry.

010

cc BG
letter only

ACOST
Advisory Council on Science and Technology
70 Whitehall, London SW1A 2AS
01-270-0426

R2/3

The Rt Hon Margaret Thatcher MP
The Prime Minister
10 Downing Street
London SW1

29 February 1988

Dear Prime Minister,

ACOST REPORT ON OPTOELECTRONICS

The Advisory Council on Science and Technology (ACOST) has recently completed a study on Optoelectronics and I have great pleasure in enclosing a copy of the final report. The study commenced under the auspices of the Advisory Council for Applied Research and Development (ACARD), but with the formation of ACOST, we decided that the subject was sufficiently important for the work to continue. The report, and its recommendations have been endorsed by the Council who have invited me to submit it to Government, and to seek your approval for publication.

Optoelectronics is the combination of optical and electronic techniques to exploit the strengths of these two separate technologies. As in any new technology, market predictions are notoriously unreliable, but conservative estimates put the world market at a minimum of £7 billion by 1990. When we contemplate a market of that size, and realise that the UK not only has an excellent scientific base in this area, but also some notable technological successes, you will understand why we are keen to see the momentum maintained and rapid exploitation of our undoubted strengths in this sector.

The report paints an optimistic picture of the UK position in this rapidly emerging technology, but warns against complacency: amongst the successes; we have pointed to some failures also. We recognise that it is unrealistic to aim for leadership in every field, and have therefore highlighted those areas where we believe the UK can make the most impact. This selection may be controversial, but I believe ACOST, like its predecessor ACARD, should not be afraid to confront industry with important choices that have to be made.

Secretariat:
Telephone 01-270 0105
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Gold 81 MPO 005

Optoelectronics is set to have an impact on the industrial and commercial life of the country similar to that of electronics over the last two decades. The difference for the UK however, is that, whereas in electronics we have been trying to catch up our competitors, in optoelectronics the UK is currently up with the leaders: we must not let this advantage slip through our fingers. I am therefore encouraged that already, the optoelectronics industry has recognised some of the shortcomings identified in the report and is seeking to remedy the situation through the formation of a group to co-ordinate their own actions. We have been impressed by the way some UK industrial sectors do this - notably the chemical industry by means of the Chemical Industry Association - and the way the Japanese do so for optoelectronics. Tony Gill, the Chairman of the study group, has therefore taken the initiative in seeking to form an industry association for the UK. He already has a great deal of support and has no intention that this should become another cosy group of industrialists meeting simply in order to bemoan their lot and whinge to Government! If you agree to the publication of this report, we hope to be able to announce the formation of an industry association to co-incide with the report's launch for maximum impact.

Optoelectronics is a technology in which the UK is well placed in world terms: we cannot afford **not** to be 'Building on our investment'.

Yours sincerely,

Francis Tombs

Sir Francis Tombs

CABINET OFFICE
70 Whitehall London SW1A 2AS Telephone 01-2XX 270 0320

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Our ref: ST 140/1

Paul Gray Esq
Private Secretary to the Prime Minister
10 Downing Steet
London SW1A 2AA

29 February 1988

Dear Paul,

ACOST REPORT ON OPTOELECTRONICS

Since the Chief Scientific Adviser is at present away in Japan (leading a mission on optoelectronics, as it happens) I am writing to let you know that the Prime Minister will shortly be receiving a letter from Sir Francis Tombs, Chairman of the Advisory Council on Science and Technology (ACOST) submitting a report on optoelectronics. His letter will request that the report be published.

Optoelectronics is a rapidly growing technology. By the turn of the century it is expected to be as pervasive as electronics is now. The UK has a sound scientific base in this area and there are a few conspicuous examples of successful exploitation. We are strong in what are currently the largest markets, telecommunications and defence, but weak in what are likely to be key areas in the future, namely consumer products and data storage.

The report focusses on industry's role in responding to these opportunities, as its title "building on our investment" implies. One of its main recommendations is for the formation of an Optoelectronics Industry Association to co-ordinate R & D and to undertake market intelligence and other work on behalf of the industry. There are similar successful models in other industries in the UK (eg the Chemical Industries Association) and in optoelectronics in Japan. The Chairman of the Working Group which prepared the Report, Mr Tony Gill, the Chairman of Lucas Industries, is very committed to this idea and is actively engaged at present in persuading firms to set up an association of this kind. So far ten major companies and a consortium of twenty smaller ones have committed themselves to establishing such a body.

As far as is publication is concerned, Mr Fairclough would certainly recommend the Prime Minister should agree to Sir Francis Tombs' request. The approach adopted in the report is generally in line with Government policy, although specific recommendations on R & D support are now rather overtaken by the new innovation policy in the DTI's recent White Paper. The recommendation on telecommunication regulation, which reflects a more substantial manufacturing industry view than was available in the Peacock Report, should also make a useful contribution to the current debate on this issue. DTI, MOD and DES (through the SERC) all had assessors on the Working Group and I understand that the three Departments would all be in favour of publication.

It is customary for Government to provide a written response to such reports. I suggest you invite the Department of Trade and Industry to take the lead in this, drawing on other Departments as appropriate, especially Education and Science and Defence.

... I am copying this minute and copies of the report to Private Secretaries to the Secretaries of State for Trade and Industry, Education and Science, and Defence and to the Chancellor of the Duchy of Lancaster with the suggestion that they should confirm to you their Ministers' views on publication and on the
... preparation of the Government response. Subject to that I attach a draft reply which the Prime Minister may wish to send to Sir Francis Tombs. Copies also go to Trevor Woolley and Richard Wilson here.

VIVIAN BROWN

DRAFT

DRAFT LETTER FROM THE PRIME MINISTER TO SIR FRANCIS TOMBS

Thank you for your letter of 29 February 1988 and for ACOST's report on optoelectronics.

I welcome the emphasis in the report on the reponsibility which industry has to build on the investment in the underpinning science and I was pleased to hear of the success which the Chairman of the Working Group, Mr Tony Gill, is having in establishing an active industry association. The recommendations for Government will require careful consideration before we can let you have a response. In the meantime I am content to accept your recommendation that the report should be published.

Advisory Council on
Science and Technology

Optoelectronics

Building on our Investment

RESTRICTED

5th Draft

Issue 5

22 February 1988

Cabinet Office

Advisory Council on Science and Technology

OPTOELECTRONICS - BUILDING ON OUR INVESTMENT

An opportunity for the UK to exploit its investment in optoelectronic technology

ACOST STUDY ON OPTOELECTRONICS

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REFERENCES

APPENDICES

A. Organisations visited or which submitted evidence to the Working Group

B. The Joint Optoelectronics Research Scheme (JOERS)

C. The Fibreoptic and Optoelectronic Scheme (FOS)

D. LINK

E. Other Department of Trade and Industry Support Schemes

F. European Programmes

G. Objectives of the RACE Programme

ABBREVIATIONS

GLOSSARY

LIST OF FIGURES

1. Copper and fibreoptic cables of equivalent capacity
2. Future telecommunications
3. Schematic diagram of a liquid crystal display
4. An advanced flat panel liquid crystal display
5. Pictures obtained by thermal imaging and conventional photography
6. Portable thermal imaging camera
7. Matrix of markets and technologies
8. Japanese tree of optoelectronic technology
9. Non-military applications of lasers

SUMMARY

A. Optoelectronics - the convergence of electronic and optical techniques - covers a broad and rapidly expanding field of materials, devices, systems and applications. Over the next 10 years, optoelectronic devices will become common, by the turn of the century supplementing many purely electronic devices in a natural progression to faster communications and greater information storage capacity. Current estimates are that the world market for all optoelectronic applications will rise to well above £7 billion per annum by 1990.

B. The report analyses the field from both market and technology standpoints to identify how the UK can best exploit its strengths and correct its weaknesses.

C. The UK has developed a strong foundation in optoelectronics research with a place amongst the world leaders in many aspects of the technology. Our exploitation of fibreoptics in telecommunications is admirable and has stimulated several UK companies to establish world-status manufacturing capability.

D. Optoelectronics is of strategic importance to our industrial base. To maintain and strengthen the UK position it will be necessary to focus the application of our R&D selectively onto accessible markets, particularly within telecommunications, computing and defence.

E. Priorities are needed to focus the efforts of industry, government, and academe on the key opportunities available to the UK: the Working Group's principal recommendations are:

i. A number of high profile demonstrator projects should be launched to show the benefits of optoelectronics and to heighten awareness of its potential across a broad front. (Section 2.2)

ii. Encouragement of the widespread installation of single mode optical fibres into commercial, industrial and domestic premises to stimulate the end-user market by the early establishment of a regulatory regime to facilitate the transport of telephony, data and entertainment services on a single network. (Section 2.1)

iii. Industry and Government support for strategic research and development in optoelectronics should be strengthened. (Sections 2.3 and 2.4)

iv. Education and training should be enhanced to ensure that staff are adequately equipped to understand the principles of optoelectronics, and to provide a pool of suitably qualified manpower for industry, government and commerce. (Section 2.6)

v. An Optoelectronics Industry Association should be formed to collect market data, develop strategic plans, act as a focal point for the initiation of research, stimulate the development of new standards, disseminate information and progress the implementation of the other recommendations. (Section 2.5)

FOREWORD

In July 1987, the Advisory Council on Science and Technology (ACOST) was established to advise government on all aspects of science and technology. ACOST absorbed the Advisory Council for Applied Research and Development (ACARD) which had been formed in 1976 to advise the Prime Minister on applied research, design and development in the United Kingdom.

ACARD had perceived that optoelectronics would become of vital importance if the UK were to retain its place as a technological nation. It was also recognised that optoelectronics was likely to impinge on all levels of society by vastly increasing the capacity to transmit, store and process information.

In April 1986, ACARD decided to set up a Working Group with the following terms of reference to study optoelectronics in greater depth:

i. To examine the nature and scope of existing R&D concerned with optoelectronics in industry and government, both civil and defence, in the UK and abroad; the way in which this is likely to develop: and to relate this to the markets in which this work is, or will be, relevant, particularly towards the end of the century.

ii. To identify ways in which the co-ordination of activity in these areas might be improved and made more effective, with resulting benefit to the UK.

iii. To anticipate the economic effects which this technology will have upon the microelectronics and other industries and the extent to which the UK, and other countries, are equipped to take advantage of the opportunities which it offers.

iv. To consider other areas in which this technology might have an impact, such as the social implications of further massive increases in available computer power.

v. To draw conclusions and make recommendations.

The members of the Working Group were:

Mr A K Gill FEng*, Chairman, Lucas Industries plc (Chairman)

Professor W A Gambling FRS FEng, Professor of Optical Communications, University of Southampton

Professor C Hilsum FRS FEng, Director of Research, GEC plc

Professor J E Midwinter OBE FRS FEng, Professor of Optoelectronics, University College London

Mr D Rogers, National Officer, Electrical, Electronic, Telecommunications and Plumbing Union

Mr P R Selway, Director of the Optoelectronics Division, STC Technology Ltd

Dr A G Slight, Technical Director, Barr & Stroud Ltd

Mr D R Smith, Director of Research, BT&D Technology Ltd

Professor S D Smith FRS FRSE*, Professor of Physics, Heriot Watt University, Edinburgh

Professor B L H Wilson OBE, Chief Scientist, Plessey Research

*ACOST member

Assessors were invited from the Ministry of Defence (Dr A L Mears), the Department of Trade and Industry (Mr J A Raines) and the Science and Engineering Research Council (Dr M Wilkins), and the Chairman was assisted by Dr P Extance from the Lucas Research Centre. The Working Group was supported by the ACOST Secretariat in Cabinet Office from which the Secretary (Mr A A Grilli) was drawn. The Group would like to acknowledge their valuable contribution to the work of the study .

The report of the Working Group was considered by ACOST in September 1987 and the recommendations confirmed when it was reconsidered in February 1988. It was submitted to the Government for their consideration and it is now published to draw attention to the Group's recommendations, and to act as a stimulus to discussion.

The Council is grateful to the members of the Working Group for their contribution to ACOST's work, and to the many companies, organisations and individuals who made contributions to the study, frequently against tight time constraints. A complete list of organisations visited and those submitting evidence is included in Appendix A.

1. INTRODUCTION

1.1 Guide to the report

This "Introduction" sets the scene, featuring three examples in section 1.3 which illustrate and emphasise the points to be made later in the report. They demonstrate the fascinating nature of optoelectronics, the opportunities which have been grasped, those which have been missed and those still to emerge.

The main sections of the report are written so as to be readily understood by those not familiar with optoelectronics. The field is analysed from two stances - markets and technologies - it is in these sections that the general reader may find occasional difficulty with the terminology. However, this should not diminish the thrust of the central conclusions and recommendations. Where possible, relevant technologies are described in the most appropriate "market" section, but when they are more pervasive and are significant across a number of fields, they are brought out separately into a "technology" section.

Abbreviations are expanded in full the first time they appear in the text, and a full list of abbreviations and glossary are annexed to the report.

1.2 The opportunity

In less than a quarter of a century, electronics has revolutionised the western world. Every aspect of commercial and industrial life has been influenced and every home invaded by this ubiquitous technology. In the next quarter century optoelectronics is poised to achieve a similar impact.

Optoelectronics is already making its presence felt. Telephone conversations are speeding across the country on beams of light. Fibreoptic cables are competing with satellite links for intercontinental circuits to provide the capacity for extra telecommunications traffic at low cost. Already a million homes in the UK have compact disc players using laser technology. Laser scanners in supermarkets read the bar codes on goods, producing fully itemised printouts and improving stock control. Lasers are in regular use in general surgery as a superior replacement for the scalpel and have enabled new techniques to be developed for treatment of eye complaints. And of course liquid crystal displays on watches and calculators have become as familiar as, and are even built into, pens and pencils.

Eventually, the exploitation of optoelectronics is likely to result in videophones being commonplace; high definition 3-D colour screens for television, one metre square and sufficiently light, compact and robust to hang on the wall; and to a computer operating with beams of light representing parallel streams of data and displaying the results without intermediate conversion into electrical signals.

Optoelectronics is the integration of optical and electronic techniques in the acquisition, processing, communication, storage and display of information. It is the manipulation of photons - particles of light, and their interaction with electrons - particles of electricity. Electrons and photons each have distinctive properties which give rise to advantages and disadvantages for particular functions. For example, photons, travelling at the speed of light, are scarcely attenuated by transparent insulators and so are ideal for long distance transmission of information. On the other hand, electrons interact strongly with each other and with most materials so can be finely controlled in ways suitable for sophisticated and flexible information processing. However, since photons can normally pass through each other without interaction, we can conceive of making optical computers with immensely more complex internal interconnections, which may therefore, be significantly more powerful than the present electronic ones.

As a result of the fundamental differences between photons and electrons, and progress in the newly developing techniques for handling both, it is quite clear that optoelectronics will impact virtually all areas of electronics over the next decade. The ultimate goal must be the optimum use of each to construct the most efficient and cost effective equipment. This poses a number of key questions:

How will optoelectronics be exploited most successfully?

What effect will this have on the market place?

How is the UK placed to benefit?

The remit of the group was to look at the future for optoelectronics, examine the UK's status in world terms and see what steps need to be taken to ensure success in this field. Reinforcing our view of the crucial importance of optoelectronics, we have noted that the Japanese have identified optoelectronics as an important growth area and have substantial programmes in place; the USA has given a great stimulus to their industry through defence procurement; and the French have large scale public demonstrator programmes in place in the form of a broadband public network in Biarritz and over two million Minitel terminals in use across the country.

Wide terms of reference were given to the Group, but it was considered unwise to attempt to investigate each in the same level of detail. We agreed that mature optoelectronics technologies such as the cathode ray tube or television, fell outside the spirit of the study, and should be excluded. Similarly, devices fulfilling a direct optical purpose were considered beyond its scope.

The social implications are not explicitly addressed in the recommendations. The explosive increase in the capacity to transmit, store and use information will have a profound effect on society as we come to terms with what can be achieved through the manipulation of data and use of knowledge. We have drawn attention to the need for a wider appreciation of the concept of using light to supplement electricity which must begin at school and continue through specialist education programmes. We believe that new concepts such as this are best introduced early.

1.3 Pertinent examples of the UK's position in optoelectronics

We have included accounts which chart the course of the developement of three key areas of optoelectronic technology where the UK has played a signicant role. For those not familiar with optoelectronics, we believe they will aid understanding, provide an insight into this fascinating emerging technology, and illustrate the degree of success - and some failure - of the UK in each field as a background to what follows.

1.3.1 Fibreoptic communication systems

This century has seen many exciting technological breakthroughs. People can travel, communicate with each other, and process information at speeds our forefathers would have thought impossible. We now take for granted many of these advances such as jet transport, global television, computers and high speed telecommunications.

As mentioned earlier, in recent years there has been a major innovation in the transmission of information. Whilst everybody is aware of the major benefits arising from the invention of the jet engine and television, few people realise the impact that fibreoptics is already having on our lives. Even fewer realise that this revolutionary concept of communicating via pulses of light travelling down optical fibres originated in the UK in the laboratories of STC (then known as Standard Telephones and Cables) about 20 years ago.

Today, the advantages foreseen for fibreoptics have been realised with the ability to transmit vast quantities of information over very long distances at economic rates. For example, a single fibre can already carry more than 12,000 telephone calls over a distance in excess of 100km at lower cost than achievable with other technologies. Fibreoptic systems are now the dominant transmission medium worldwide for long haul telecommunications, and a quarter of a million miles of optical fibre cable have been installed in the UK alone over the last 7 years. Over this period the UK has maintained a leading role worldwide. This has resulted from a strong R&D base which has been exploited by the enlightened procurement policies of British Telecom (BT) in the modernisation of its transmission network and by UK export successes in the submarine cable business.

However, the fibreoptic revolution has only just begun. Over the coming decade there will be an increasing penetration of optical fibre, into both industry and the home, bringing an extensive range of new services. It will be possible, in the near future, for a single optical fibre to provide an integrated range of low cost high quality telephony, data and entertainment services far exceeding those available today.

This enormous new market opportunity has been recognised by all of the major industrialised countries, many of whom have rapidly established highly competitive R&D and manufacturing capabilities. The vital question now is whether the UK possesses the R&D and manufacturing strengths to meet this challenge, matched by the political and economic climate to ensure further success? To answer this question, it is first necessary to examine the reasons behind the UK's current successful position.

Fibreoptic systems have required the parallel development, over a number of years, of several key enabling technologies; namely, highly transparent silica optical fibre and highly efficient and reliable tiny semiconductor lasers and detectors. During the 1970's and early 1980's the UK had strengths in all these areas as a result of co-ordinated programmes by the Ministry of Defence (MoD) and BT in supporting R&D in industry, together with further innovative research from Universities. BT's research laboratory was a world leading R&D centre for fibreoptic research in both components and systems comparable with Bell Laboratories in the USA and Nippon Telephone and Telegraph (NTT) in Japan. Currently, BT remains a world leader in the field, but support for R&D in optoelectronics companies by both BT and MoD has declined rapidly in recent years. This has been partly offset by a Department of Trade and Industry (DTI) and Science and Engineering Council (SERC) initiative which supported research on optoelectronics through the 'Joint Opto-Electronics Research Scheme' (JOERS). In addition, the DTI 'Fibreoptic and Optoelectronics Scheme' (FOS) offered strategically targeted assistance for product development between 1981 and 1987. Companies participating in these schemes provided the majority of the funds for projects and there are many current programmes in industry not receiving government financial support.

A successful example of 'FOS' support was for R&D in undersea transmission systems. STC held a dominant position in world markets for copper cable undersea systems but, by the late 1970's, it became apparent that fibreoptics would supplant copper technology. A multi-million pound investment was essential to maintain market share. Financial support from DTI, allied with technical support from BT, underpinned the extensive research and product development programmes for the ultra-high reliability components. This activity was necessary for STC to continue as the pre-eminent supplier to the world market, a position which it still retains.

COPPER AND FIBREOPTIC CABLES OF EQUIVALENT CAPACITY

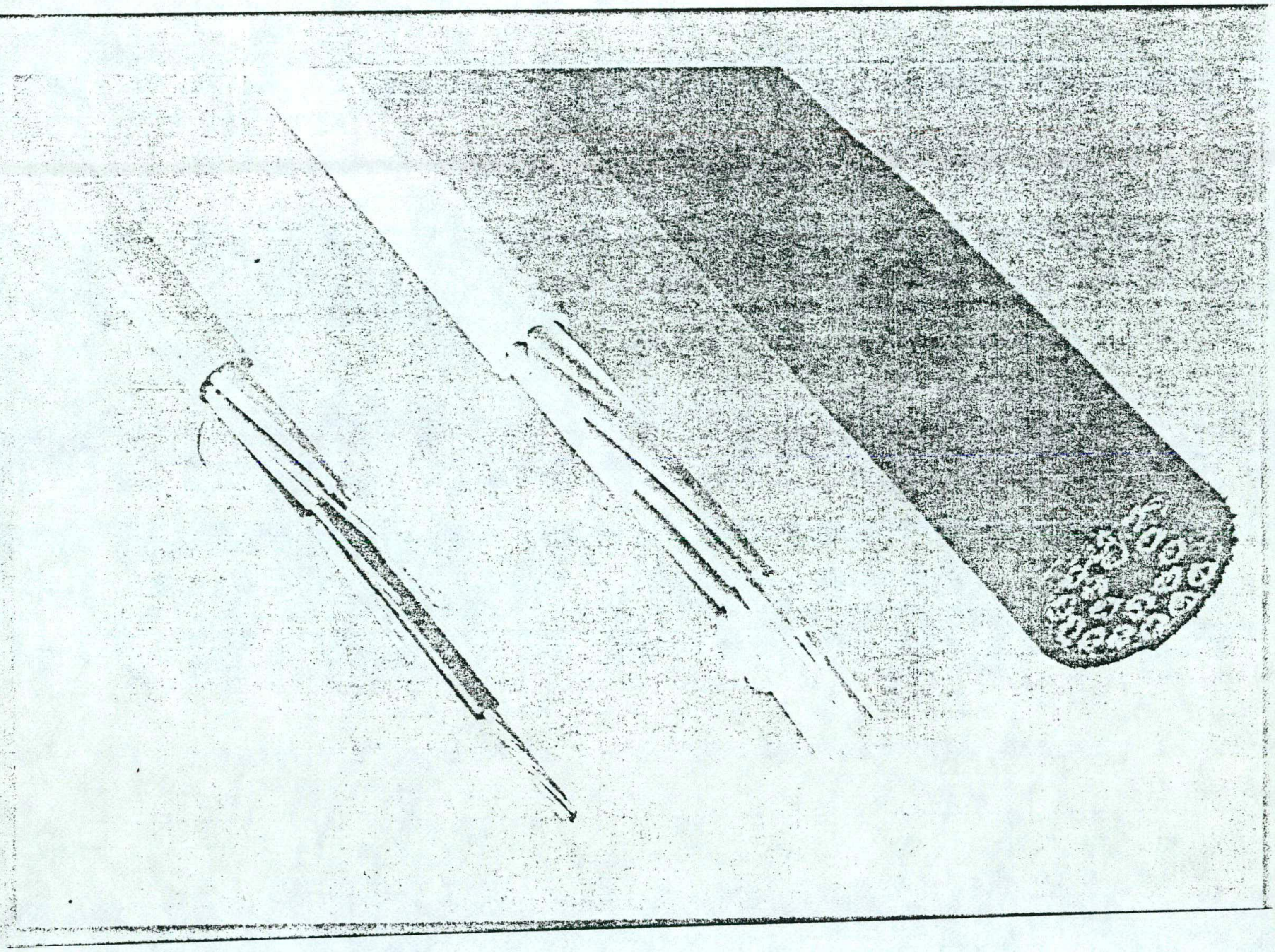

Figure 1

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FUTURE TELECOMMUNICATIONS

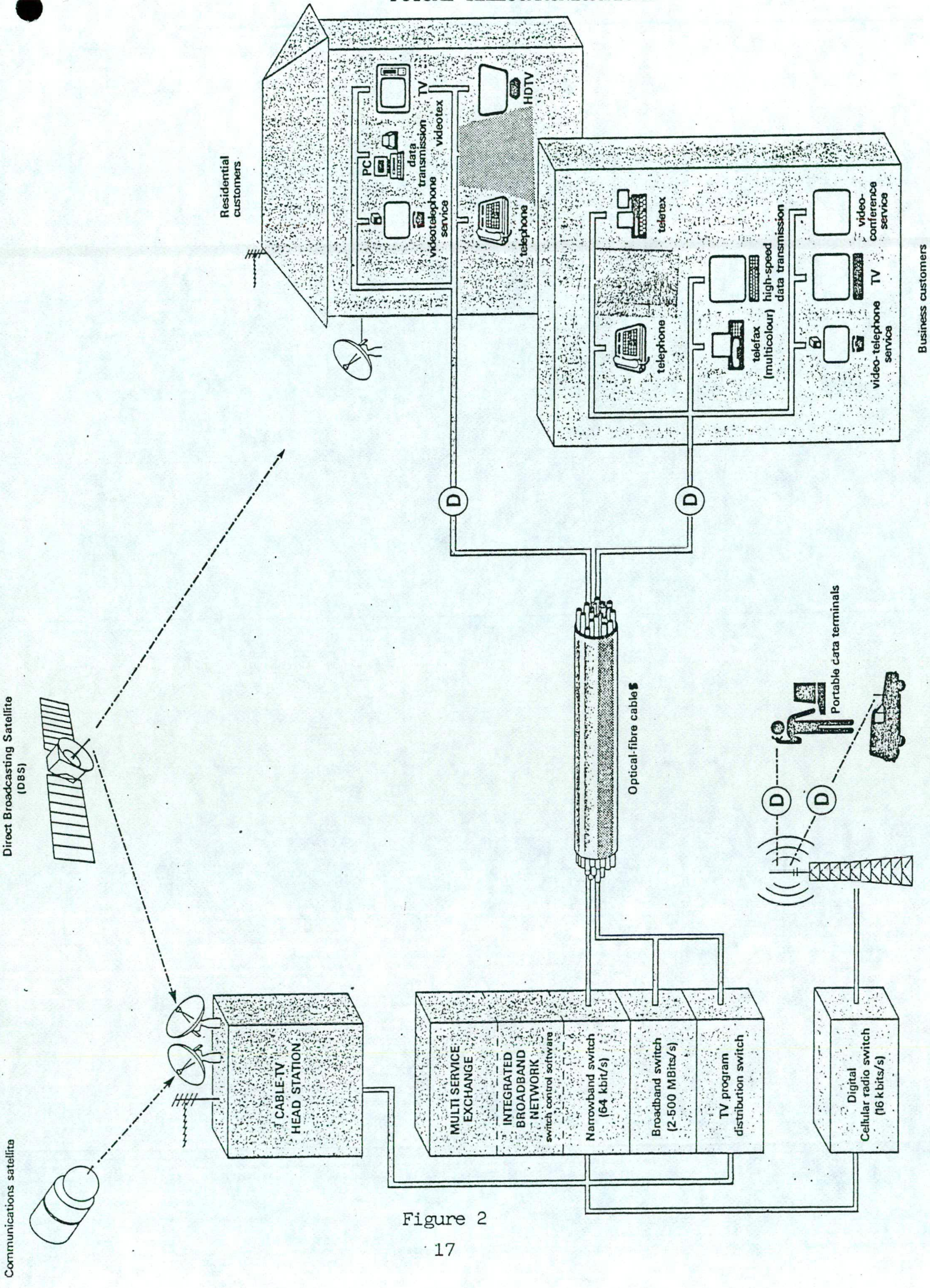

Figure 2

The UK has an excellent position in low cost fibre and cable manufacturing, but a similar position must be established in the volume production of complementary low cost optoelectronic components and subsystems. In addition, a strong indigenous market is needed to provide a base from which to launch UK companies as leading suppliers to the worldwide market. For UK industry to become a major competitive worldwide supplier in a wide range of fibreoptic telecommunications equipment, significantly higher investment in research, development, and production is needed.

Government, service suppliers, financial institutions and industry need rapidly to reach a common view on how the market can be stimulated to benefit the UK through an appropriate regulatory environment, technical standards and investment levels. The ultimate reward will be a fibreoptic-based communications infrastructure (see Figure 2) - with its attendant advantages - and a healthy UK industry which can supply both services and systems, competing effectively against worldwide competition.

1.3.2 Liquid crystal displays

Liquid crystal displays are familiar to all of us through their use in watches, clocks and calculators. Liquid crystal materials were discovered almost 100 years ago, but interest in them only developed in the late 1960's, when it was shown they could be used in flat panel displays. By 1970 over 3000 different materials were known, but all were poor candidates for either commercial or military applications. Most operated only at temperatures too high for practical purposes, and the few that did work at room temperature were degraded by water vapour or decomposed by sunlight. At this time the main centres for work on liquid crystal materials and devices were in Japan and the USA, but the UK had no effective programme.

SCHEMATIC DIAGRAM OF A LIQUID CRYSTAL DISPLAY

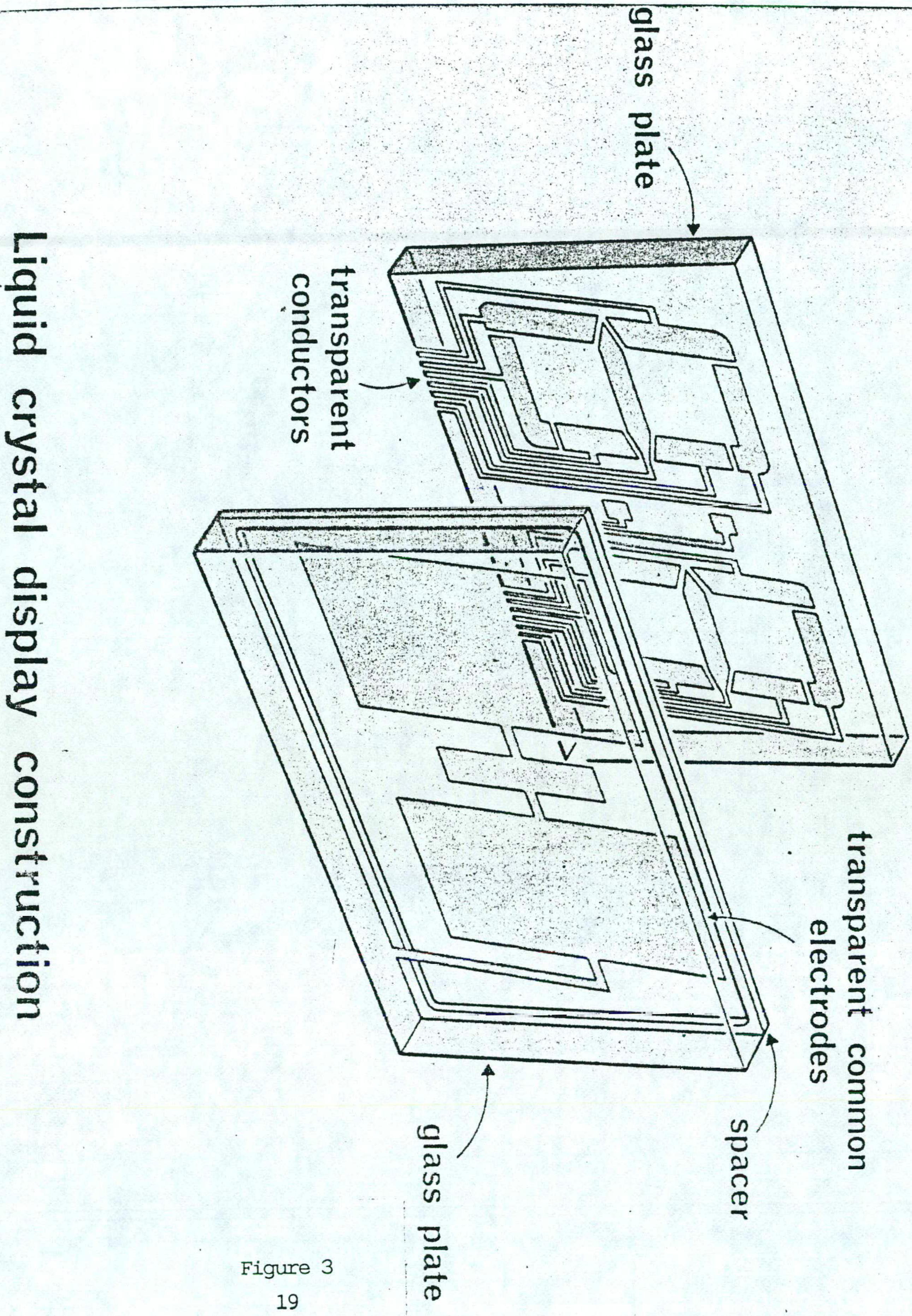

Figure 3

The essential features of the most common liquid crystal display is shown in Figure 3. A thin layer of liquid crystal material is held between two sheets of glass with transparent electrodes on the glass inner surfaces, and a polarising sheet on the outer surface. Light radiation consists of two vibrations at right angles to each other, and the polarising sheet trasmits only one of these. The liquid crystal in the cell twists the vibration direction through 90 degrees, so that if the two polarising sheets have their preferential directions parallel, no light can penetrate, and the display looks dark. When the cell is switched on, by the application of a low voltage, the 90 degree twist is removed, and now light can be transmitted, so the cell looks bright.

In practice the activation is localised by etching the conducting layers on the inner surfaces of the glass walls into segments. Each segment acts as a separate electrode, and a bright region of the display appears beneath any segment to which volts are applied. For the presentation of numbers, seven segments are normally used, arranged as a figure eight. By activation of the appropriate segments, any number for 0 to 9 may be obtained. For letters, 35 dot segments in a 7 x 5 matrix are needed.

In 1970, the need for flat panel displays for military applications, together with concern over the import of electronic devices led to a reassessment by MoD of their work on displays. As a result a collaborative research programme was established between RSRE and Hull University.

Hull University identified the basic cause of instability and synthesised a new family of materials which had the desired stability, response time, and low operating voltage. The problem remained that no one material would retain these properties over the required temperature range of -10 to +60 degrees Celcius. The key was to make suitable mixtures, but the number of conceivable combinations was much too great to embark on a random search.

It was here that RSRE scientists made a crucial contribution by devising the method of predicting the properties of the mixtures of materials from the thermodynamic parameters of the individual components. Theoretical and experimental work clearly indicated that further developments of the individual components was necessary. This was successfully undertaken at Hull University, and so the first generation of liquid crystal materials, suitable for watch and calculator displays, was born.

AN ADVANCED FLAT PANEL LIQUID CRYSTAL DISPLAY

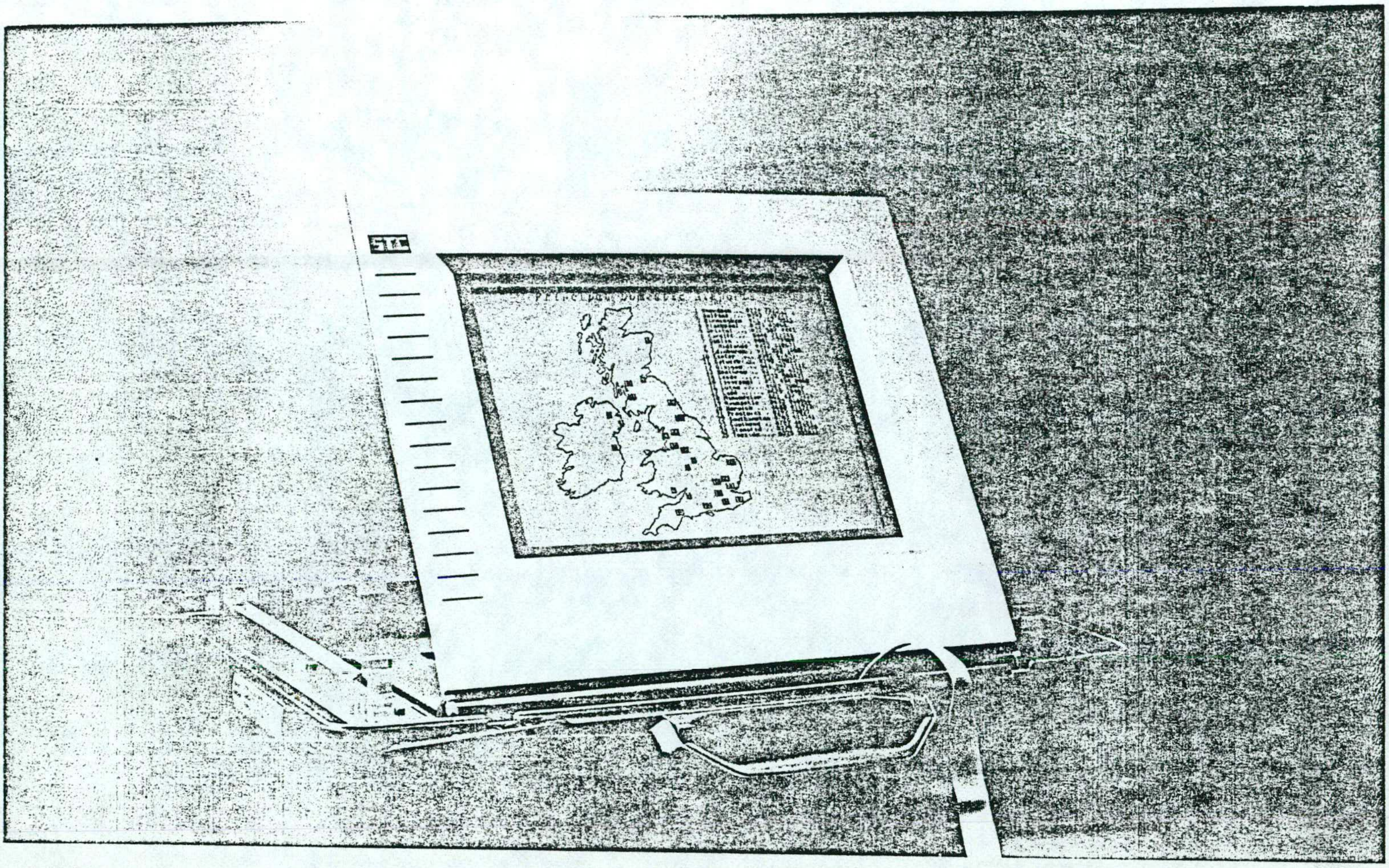

Figure 4

The materials and mixtures were patented in 1972 and passed to BDH Chemicals Ltd, a company experienced in the production of ultra-pure organic chemicals. The contribution of BDH was to devise and develop methods of synthesising materials to the required level of purity, economically, on a commercial scale, and with the technical assistance of RSRE, to market the materials on a worldwide basis.

By 1977 BDH had 50% of the world market for materials, worth over £1 million. Further technical developments were necessary to develop materials suitable for larger displays, which employ a more complex form of electronic control. This was achieved through the same collaborative approach and, by 1981, BDH's sales of liquid crystal materials had doubled to £2.5 million. Despite the emergence of competitors in the field, the UK-designed and produced materials are still regarded as the best in the world.

Regrettably, although the UK has been successful in specialist display markets, it has not been successful in converting its lead in the basic materials technology into a share of the much larger world market for complete displays, currently estimated to be in the region of $1 billion. The reason for this is largely a result of decisions by UK industry in the mid-1970s not to invest in the large production capacity needed to take part in this very competitive and risky market, but to concentrate instead on smaller specialist markets with higher unit costs and higher margins. A contributory factor may have been the general lack of the key relevant production engineering skills in the UK.

However, the fundamental understanding of the requirements of liquid crystals, the innovative work at Hull University and RSRE, with the evolution of commercial chemical manufacturing methods, have laid the foundations for further development of materials to match the changing demands of the end-users. A new generation of display technology is being researched and this presents the UK with a new opportunity in flat panel information and TV displays. The successful exploitation of this new work will, once again, depend on investment in production capacity.

1.3.3 Thermal imaging

Being able to see at night or through mist and smoke would be useful to anyone, but it is especially important for defence. When military aircraft streak down valleys and over hills at tree-top height, the pilot can see his surroundings as well by night as by day, thanks to thermal imaging. The world as seen through a thermal imager is different from a visible picture, but as Figure 5 shows the thermal picture is just as clear, and indeed often clearer and more revealing. Today thermal imagers are being increasingly adopted in all areas of defence - air, land and sea.

In the first World War, the British scientist, Lord Cherwell, first proposed that aircraft and ships could be detected using infra red thermal radiation. Though everything emits thermal radiation continuously, the problem was to find a way of detecting it. In the second World War, simple infra-red detectors were developed to enable the RAF to identify friendly aircraft at night. After the war, research continued at what is now RSRE to find materials that could detect infra-red radiation at long wavelengths in order to see relatively cool things, such as the human body and countryside. An important breakthrough came in 1958 when the scientists discovered a new material cadmium mercury telluride (CMT) which was to become the key to high performance thermal imaging. But CMT proved a very difficult material to produce, and in the early 1960s interest in thermal imaging declined. However, a small programme continued quietly and in 1966 the UK produced the world's first demonstration of real time thermal imaging.

To progress from the early primitive detectors to the manufacture of today's high performance imagers required much research, original thinking and many inventions and developments - from RSRE and more than 10 UK companies who joined the programme in the 1970s, working together in close collaboration. The military strategy was also important. Because of diverse military requirements, there was a danger that each part of MoD would develop its own thermal imager, causing duplication and waste. MoD analsysed its requirements and concluded that they could be met by just two classes of standard modules; small man portable modules and larger ones with higher performance. These modules have now been adopted widely in British systems and also sold to 17 friendly countries around the world.

PICTURES OBTAINED BY THERMAL IMAGING AND CONVENTIONAL PHOTOGRAPHY

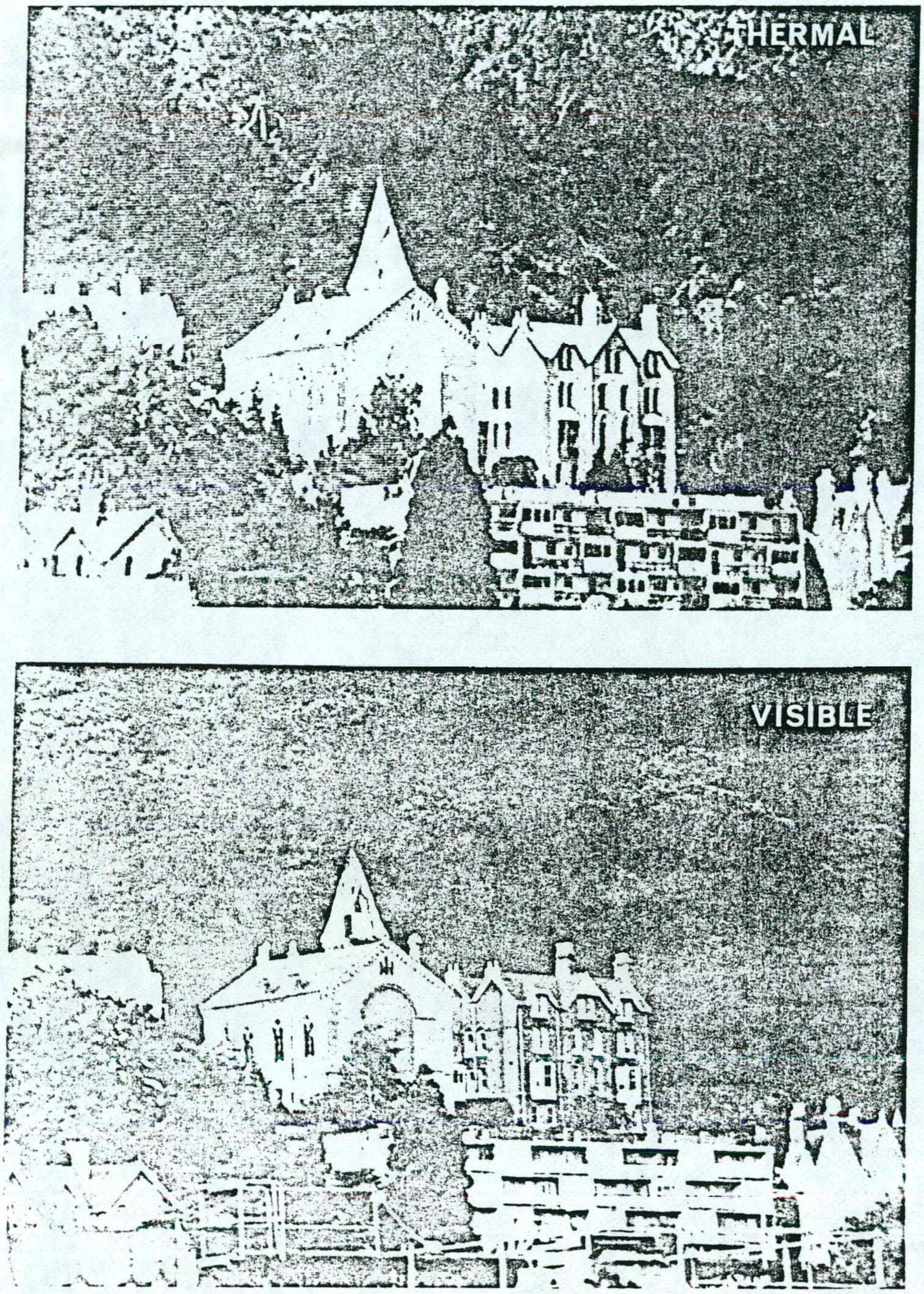

Figure 5

Alongside CMT, another class of detector materials was being studied in the late 1960s. These were pyroelectric materials which could convert a heat image directly into a pattern of electric charge. The major problem to be solved was that changes in temperature of the material due to the incident thermal radiation were incredibly small - about one ten thousandth of a degree. A large number of new materials were produced and tested to find some with an acceptable combination of pyroelectric, dielectric, thermal and fabrication properties. From this work pyroelectric detectors and imagers were developed in the 1970s from a co-ordinated MoD/industry programme. There is now a growing UK business for the manufacture of intruder alarms using simple pyroelectric detectors and for pyroelectric imagers used by fire brigades to see through smoke (Figure 6) and by navies around the world for firefighting on-board ship. Pyroelectric imagers cannot produce the same quality of picture as CMT imagers, but they are simpler and much cheaper.

Overall, to develop thermal imaging the UK has spent around £100M on R&D. UK sales of thermal imaging components and imagers are currently about £40M per annum, but this does not include sales of whole systems which depend for their effectiveness on having high performance thermal imaging within them. Advanced technologies such as thermal imaging are a small but important ingredient of the continuing export success of the UK defence industries.

Since 1983, the same teams have been working to produce much cheaper thermal imagers, so that these are affordable, not just systems for military applications, but also in markets such as medicine, safety and industrial inspection, search and rescue, pollution monitoring and robot vision.

PORTABLE THERMAL IMAGING CAMERA

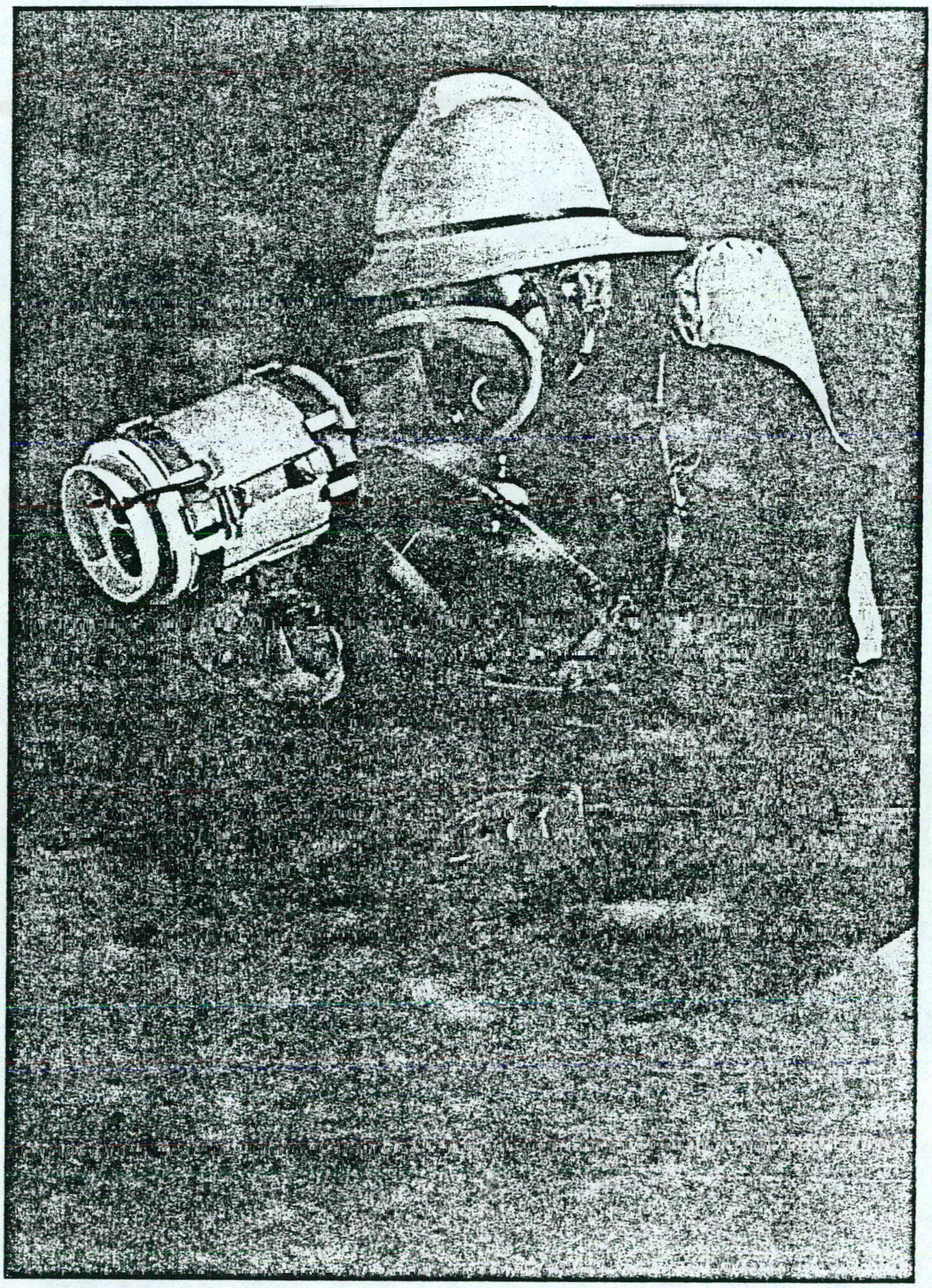

Figure 6

2. CONCLUSIONS & RECOMMENDATIONS

Optoelectronics is vital to our future as an industrial nation.

The opportunities for exploitation of optoelectronics are immense. This is recognised by our major industrial competitors who have mounted various initiatives to stimulate their own industries. Despite previous UK Government support, we believe that the scale of current work does not match the opportunity.

2.1 Large scale installation of optical fibres

By far the greatest stimulus to the market for optoelectronic systems and products would be, we believe, the early installation of single mode optical fibres into every commercial and domestic property in the UK. This is close to being technically and economically feasible. The benefits extend far beyond the opportunities for UK suppliers to export such systems. The provision of such a network would enable the UK to be in the vanguard of a revolution in communications, which will penetrate into - and confer benefits on - many aspects of the nation's life; most obviously telephony, teleconferencing, videophone, TV, data transmission, electronic funds transfer and file transfer, but further into publishing, education, libraries, newspapers and other services. These in turn will stimulate new industries and opportunities.

The Committee on Financing the BBC chaired by Professor Alan Peacock which reported in July 1986 (1) recommended that "national telecommunication systems (British Telecom, Mercury and any other subsequent entrants) should be permitted to act as common carriers with a view to the provision of a full range of services, including the delivery of television programmes." We recognise that this recommendation leaves unanswered many important issues - particularly the maintenance of a competitive environment to drive forward installation at the maximum rate and the implications of such a decision on the fledgling cable television operators.

However, we believe that the potential importance of the effect of these changes in the regulatory environment is such that the Government should resolve them as a matter of extreme urgency. This should be done as soon as possible once the study currently under way, by the Department of Trade and Industry (DTI), on the future infrastructure of electronic communications in the UK is completed.

We therefore recommend that the Government investigates options for changes in the regulatory framework controlling national telecommunications systems, with a view to encouraging the widespread installation of single mode optical fibres into commercial, industrial and domestic premises, in such a way as to stimulate the indigenous optoelectronics industry whilst maintaining a competitive environment.

As a precursor, **we recommend that the opportunity be offered to British Telecom, Mercury Communications and Kingston-upon-Hull City Council, each to mount independently, or in collaboration with other parties, a large scale pilot project to procure systems for the delivery of entertainment, telephony and data traffic over a single integrated fibreoptic network to commercial, industrial and domestic properties.** This would enable some of the current architectural models to be tested on a realistic scale; enable partnerships to be developed; provide UK suppliers time to organise themselves into competitive consortia; avoid conflict with existing cable operators' areas; and maintain a measure of competition. To ensure that the system embodied the best technology, specific technology demonstrators should be supported by Government.

To derive the desired benefits, the networks would have to aim for 10,000 to 100,000 subscribers each, with well defined targets for cost per subscriber. Government assistance would most probably be required for some aspects of such an ambitious project, but we see governments in other countries - most notably France, West Germany and Japan - mounting similar initiatives, in order to create an early market in optoelectronics to stimulate the establishment of large scale production facilities to bring down the costs of components, to test architectural models and to assess the pattern of usage of novel services. Under such circumstances, UK companies will find it difficult to compete against the international competition without this embryo home market created as we propose.

A novel approach to these demonstrators would be to view them as infrastructure provision, and hence to provide assistance for the projects to be undertaken in depressed areas. In some instances, European Community assistance might be negotiated (as in the STAR Programme).

A particular opportunity arises in this area for Government to take a lead by establishing a broadband network to connect its own buildings in central London. In addition, the Government have a large number of establishments widely dispersed around the UK which routinely wish to communicate and transfer data between one another. Fibreoptic networks to facilitate these communications would be a high-profile, far-sighted investment and intrinsically more secure than existing system. The inherent security of fibreoptics could be supplemented by encryption, yielding further opportunities for subsequent commercial exploitation.

2.2 Technology demonstrators

In addition to the major stimulus for telecommunications procurement, a number of specific technology demonstrators are proposed. Without a broad technological base and thriving component supplier industry, the major systems suppliers cannot prosper. The concept of technology demonstrators has been shown in other areas to be particularly effective, in stimulating the development of the necessary constituent parts and giving a high public profile to complete systems, creating confidence amongst potential customers and generating sales. Previous examples of international telecommunications fibreoptic cable demonstrator projects, between the UK and the USA and between the UK and Belgium, have been notably successful in highlighting the technological capabilities of the UK and stimulating further business.

We therefore recommend that the Government, in partnership with industry, encourages a series of high profile demonstrator projects to illustrate the applications of optoelectronics across a broad front. This would also serve to increase awareness of the importance of optoelectronics to all sectors of industry. Where appropriate, these demonstrators could be mounted by means of enlightened public procurement or integration with other applications initiatives. Previous demonstrator projects in optoelectronics (eg landbased and submarine fibreoptic communications systems) have established world class production facilities in the UK.

Examples of potential demonstrators could be:

i **Telecommunications components:** A wideband optical switch for a group of subscribers; terminal equipment such as a domestic/small business fibreoptic terminal; and an optoelectronic entertainment centre which could access a variety of services.

ii **Optical interconnects:** An early computer or telecommunications demonstrator should illustrate advanced equipment practice for connecting circuit boards and be followed by a more ambitious project showing optical interconnection between individual integrated circuits.

iii **Process control and instrumentation:** The demonstrator could be large scale - monitoring and control of a complete process plant - or small scale - a totally integrated optoelectronic measuring instrument - depending on the perception of the most promising market opportunity for exploiting the safety and other advantages of optical devices.

iv **Safety and security:** A system exploiting the inherent advantages of optoelectronics, especially sensors, transmission and processing techniques, to monitor fire and personnel safety, together with intruder detection.

v **Flat panel high definition television:** There will be a tremendous world-wide market for high definition television with at least 1125 lines, up to one metre square, less than 150 mm deep, robust and light enough to hang on a wall.

vi **Optoelectronic paperback:** The 'Walkman' style of portable cassette/radio has proved surprisingly successful. A similar project using compact disc, or a credit card size optical storage device, as the data source with low-power optoelectronic display could provide an electronic book including sound, packaged with the portability of a 'Walkman'.

vii **Medical:** The medical market offers a host of possibilities typified by laser-based imaging techniques to examine teeth as an alternative to X-rays; lasers in dental practices for oral surgery, treatment of caries, and enhanced tissue healing; and health care information systems exploiting the massive storage potential of optical techniques.

viii **Classroom:** Allied to a later recommendation concerning education and training, the equipping of a room or laboratory in every school with an optoelectronic system, to demonstrate some applications of the technology - the precise nature of the equipment being determined by links created with local industry and higher education establishments.

2.3 Development and exploitation

Development and exploitation are clearly the province of industry. In the past, considerable stimulation and finance has been provided through the various programmes of BT, MoD and DTI. The demonstrator projects described in the earlier sections will go some way to maintain the momentum previously supplied by BT and MoD, but we believe that it is essential to retain a mechanism to encourage and assist both collaborative and non-collaborate projects in industry. In many areas, the markets are not sufficiently developed to generate the sales necessary to finance investment at the appropriate level.

We therefore recommend that selective support for the development of optoelectronics products is continued together with special facilities for small firms similar to those previously available under the DTI Pre-production Order Scheme as advocated in a Report by the Technology Requirements Board (2).

2.4 Research

Historically, the MoD Directorate for Components and Valves Development (DCVD), and the then public sector British Telecom (BT) have been major driving forces behind the research, development and exploitation of optoelectronics. As MoD has narrowed its focus and BT has moved external research work in-house, the Science and Engineering Research Council (SERC) and DTI have increased their contribution to medium term, long term and collaborative research. Industry also responded with its own investments, but many companies have been cautious in conducting R&D on the scale necessary to exact a good return in a rapidly growing but price sensitive market, particularly in telecommunications because of uncertainty over future procurement policies. The importance of strategic research has been commented on before, notably by the House of Lords Select Committee on Science and Technology (3) the ACARD report "Exploitable Areas of Science" (4), and more recently by the Government White Paper on civil R&D (5). We believe that in the absence of any proven alternative mechanism for filling this gap, the urgency of the task requires that Government continues to stimulate activity in this sector, encouraging industry to increase its R&D and to keep the UK abreast of its international competitors.

The Joint OptoElectronic Research Scheme (JOERS), financed jointly by industry, DTI and SERC, is welcomed as having been effective in fostering successful collaboration between many competing companies and in encouraging an increased degree of industry/university collaboration. However, because the demand for project funding has been much greater than the financial allocation, many extremely attractive proposals have not been supported.

The recent LINK initiative is also relevant, but we believe that the impetus for continued and improved research and development in optoelectronics should be enhanced and the momentum retained under JOERS, even if this then becomes related to LINK and/or other schemes.

We therefore recommend that the Government extend and enhance JOERS and devote additional resourses to it. Co-operative research activities in industry should continue to be eligible for up to 50% funding, although higher rates would be appropriate to stimulate smaller companies and, in exceptional circumstances, where the benefits accrue to the whole UK community, rather than solely to the organisations undertaking the research. Taking note of the recent DTI Enterprise Initiative, we would have preferred to have seen DTI continue schemes for single company research, with a high priority accorded to optoelectronic applications, and consideration given to increasing the level of support above the previous 25% level. Judgement of the new 'Research and Technology Initiative' will have to be reserved until the scheme has been allowed sufficient time to prove itself.

We believe that research carried out in universities and polytechnics should continue to be funded at 100%, and **we recommend a further shift in the balance of SERC funding within the Science and Engineering Boards towards optoelectronics.** In particular, centres need to be established to produce and investigate the properties of new materials, novel device structures and fabrication techniques. The UK cannot afford multiple facilities for such research and resourses must be concentrated to avoid dilution of effort. We therefore support the general thrust of the ABRC Strategy for the Science Base (6) that research needs to be concentrated in centres of expertise to avoid spreading our scarce resourses too thinly, although this should not preclude new ideas emerging from outside of those centres. In optoelectronics, this concentration has already largely occurred, but **we recommend that SERC include more optoelectronic technologies in their priority areas for the establishment of Interdisciplinary University Research Centres.**

Overall, we believe that SERC's activities in optoelectronics would benefit from closer co-ordination through the formation of an Optoelectronics Directorate, as has been done for example, in the case of biotechnology. If appropriate, consideration could be given to mounting such an initiative with synergistic technologies such as microelectronics, to capitalise on the common features of the technologies in certain key areas. **We therefore recommend that SERC consider the establishment of an Optoelectronics Directorate to draw together more closely its relevant activities.**

2.5 Industry Association

We consider that a major weakness of the optoelectronics sector in the UK is the absence of a suitable and dedicated organisation to collect market data, develop strategic plans, act as a focal point for the initiation of research, stimulate the development of new standards, and disseminate information. **We therefore recommend that UK industry should form an Optoelectronics Industry Association (OIA) to draw together all those active in the sector to:**

a. Commission studies into the long term market trends to help industry and Government formulate plans and set objectives.

b. Ensure that knowledge of current research and development is disseminated widely to fuel productive co-operation and avoid duplication of effort.

c. Enable a dialogue to take place between component manufacturers and system builders; large, small and medium size enterprises; and suppliers and users.

d. Act a central focus for consultation on standardisation issues and stimulate the development of new standards where they are deemed necessary.

e. Make representations to government concerning actions which would promote the interests of optoelectronics equipment suppliers and their major customers to the benefit of the whole economy.

f. Act as a clearing house for enquiries on UK suppliers of optoelectronic systems, sub-systems and components.

The model and stimulus for this recommendation is the Optoelectronic Industry and Technology Development Association in Japan (OITDA). There are good reasons for believing that such an association would be effective and very beneficial. There are precedents in the UK; for example, the Chemicals Industry Association (CIA) with a membership of around 200 companies serves a very successful industry. We believe that a similar body in the UK for this new and emerging field would fulfil a catalytic role and enable the UK to develop a strategy to capitalise on its undoubted research strengths. We sought industry views on this proposal and were encouraged by the reception to pursue the idea. To-date, ten major companies plus a consortium of 20 smaller companies have committed themselves to establishing such a body.

It is envisaged that Government Departments concerned with optoelectronics would take an active part in the organisation.

In addition to the general tasks listed above, we see that such an agency would address the following issues raised within the report as a matter of urgency:

A. Co-ordinate industrial contributions to EC and other international collaborative programmes to ensure that strong consortia are established to bid for contracts.

B. Advise government research establishments on research programmes for optoelectronics to ensure that they are geared to the needs of industry.

C. Provide an industry focus for liaison with DTI to advise on priorities.

D. Advise government on ways of promoting the interests of UK industry through enlightened public procurement policies.

E. Catalyse convergence between broadcasting and telecommunications standards activities.

F. Advise SERC on co-ordination of their optoelectronic activities.

G. Examine ways by which the UK can participate more fully in the optical data storage market.

H. Follow up the recommendations contained within this report directed at education and training requirements.

2.6 Education and training

As with any new technology, the supply of qualified manpower tends to lag behind the demand. The need for an adequate supply of suitably trained engineers and technicians in the electronics and IT industries has been commented upon on many occasions and in many other places, and therefore we have not dwelt on it excessively in this report.

However, there is a general requirement that the education system should appreciate the needs of their students throughout their working lives rather than merely react to current skills shortages. Those emerging from the education system are the new people in the jobs market and therefore need to be equipped to fill the new jobs which emerge. Many of these will be created in new high technology industries like optoelectronics. A dialogue must therefore be maintained to ensure that changes to curricula reflect emerging requirements in science and technology, but courses must first and foremost provide a thorough grounding across a broad spectrum of science to equip pupils for future developments in technology.

We are particularly concerned at the reduction in emphasis on the teaching of 'optics' within science curricula at the very time when its importance in technological terms is increasing dramatically. Section 6 contains a number of detailed recommendations aimed at remedying that weakness.

The situation in optoelectronics at technician, graduate and post-graduate level is more encouraging, and we commend the many initiatives currently under way. A number of detailed recommendations for further improvement are contained in Section 6, including a reference to the need to enhance our capability in micro-mechanical engineering, an essential skill in relation to optoelectronics and many other modern fields of application.

We also share the views of several other groups in calling for government to reconsider the establishment of a mechanism to bring to bear external advice, especially an industry voice, to the educational system. We see this as an essential customer-supplier link. Until such a channel exists, the Optoelectronics Industry Association outlined in the previous section could provide the necessary link between industry and education to pursue the recommendations contained in this report.

3. MARKETS

3.0 Overview

The markets for optoelectronics are very diverse and need discussion in some depth to understand the motivation for many of the technology developments. This overview introduces the more comprehensive discussions later in the section and paints an overall picture of the marketplace. The subsections describe the market areas in which optoelectronics is expected to have an impact in descending order of importance. Broad themes emerging from a number of market and technology sections are drawn together and considered in section 7 COMMENT.

The four major markets having the largest volume and providing the major stimulus to technological development are communications, information systems, consumer and military. Three medium size markets were identified where the technology initiated by the major markets has significant opportunities for development and exploitation, namely automotive, aerospace and medical. Specialist technology will also be important in these areas, particularly in the medical field. Finally four smaller markets are discussed which either comprise more restricted use of optoelectronics in niche areas, namely materials processing and energy, or represent smaller scale use of a wider range of optoelectronic technology again commonly building upon developments from the major markets.

There is a paucity of data with which to measure the performance of the UK in optoelectronics, as indicated in a number of sections of the report. Where possible, marketing information has been included to place in context the size of the opportunity, but it is recognised that definitions and bases of the statistics differ from one section to another, and that there is inevitably some measure of double counting.

3.0.1 Major Markets

3.0.1.1 *Communications*

Demand for electronic communication will continue to expand rapidly during the next 20 years. One driving force is the increasing use of comuputer networks and computer-based financial and information systems throughout all sectors of the economy. Also, as communication costs decrease, other market sectors will open up, such as extensive use of video conferencing, video telephones, high definition television, and other services.

Most of this expanding communications market is likely to be filled by optical fibres communications, though satellites will offer a degree of competition, governed by cost. The trunk optical fibre networks that can handle these services are already largely in place in the UK. However to meet the demands of small businesses and of the consumer market, local optical fibre networks must also be installed. This in turn may depend on changes in the regulatory framework as discussion in the Peacock Report (1). Demonstration projects will be important to stimulate demand and to understand these markets in greater depth.

The world market for telecommunications equipment (ie excluding broadcasting etc) is about £100 billion and predicted to grow at a compound rate of 10% until the turn of the century. Within this, the UK market for all communications equipment is £20 billion. The optoelectronic content is difficult to estimate accurately, but the potential for the infrastructure alone assuming a capital cost of £200 per subscriber could be £300m pa in the UK and £900m pa for the rest of Europe. By comparison, in 1985 the value of the production in optoelectronics for communications in Japan was £1500m. However, the total business generated by these activities is several times the infrastructure figure.

3.0.1.2 *Information systems*

The only optoelectronic component in early computers was the TV monitor display. But this situation is changing rapidly, as speed of processing, data storage and aesthetic factors develop. Whilst the conventional TV-like display remains dominant, liquid crystal displays (both monochrome and colour) are gaining market share - particularly for portable machines. Less obviously the use of optoelectronics in data storage, using technology akin to the compact disc player, is becoming important where large amounts of data need to be stored indefinitely without alteration. Erasable storage media will vastly increase the penetration of optical data storage. Even less obvious to the user of computers is the use of optical technology for interconnection between machines, eg local area networks, or within a machine - for rapid transfer of data. Within the computer short optical links using optical fibres, or even holograms, can enable very fast processing speeds to be achieved. In the longer term extremely high processing speeds will be obtainable using optical processing (ie by performing many calculations at the same time using a single light beam with no electronic components), and this will become important - particularly in image processing applications.

Other applications within this market area include high quality document preparation systems commonly using laser printers, based on semiconductor lasers and the Xerox process, and the all pervasive bar code reader for the retail sector.

The total world market for information systems, aggregated from sectorial analysis indicates a figure in excess of £100 billion. Estimation of the optoelectronic portion is particularly difficult to attribute as the technology of computers and their peripherals is changing rapidly and precise values depend on the definition of what constitutes the 'optoelectronic' content. Nevertheless, however it is defined, it will amount to tens of billions of pounds per annum by 1995.

3.0.1.3 *Consumer*

The UK does not have a good record for exploitation of electronics technology in the consumer sector. At present, the same criticism could be levelled at optoelectronics. The development of flat screen solid state displays for television will be the largest market within this sector. Sophisticated optoelectronics are also used in the compact disc player, where a semiconductor laser is used to read data from a reflective disc that is decoded into very high quality sound. The market is characterised by the need for strong marketing and rapid innovation and may therefore be stimulated by a high profile demonstrator.

As an example to indicate the size of the potential markets the annual UK sales value of compact discs and compact disc players in 1990 is predicted to be £25m and £140m respectively (roughly 1/20 of the world market). The extension of this technology to video may yet occur - despite the preponderance of video-tape machines as the demand for video products and interactive video service increases.

3.0.1.4 *Military*

A major application of optoelectronics that has been almost exclusively developed for military purposes is night vision and infra-red imaging. The military importance of such sensors is very considerable, and for the forseeable future there will be a strong market for new generations of equipments providing higher performance and lower unit cost.

A second important and expanding defence market is in information systems, particularly for command and control, and for surveillance, target acquisition and intelligence. The future world market for military communications sytems exploiting fibreoptics could exceed £1 billion per annum, and there is also a major defence market for high performance information processing, data storage and displays.

A third defence market is for laser systems particularly for rangefinding. This market is several hundred millions of pounds per annum worldwide, around £50M per annum for the lasers themselves.

The present value of the total military market for optoelectronic components and systems is of the order of £2 billion per annum in the western world, about half of this being in the USA. During the next decade, optoelectronics will account for an increasing portion of the total defence market.

3.0.2 Intermediate Markets

3.0.2.1 *Automotive*

The automotive market is characterised by the very low unit cost of electronic systems and the harsh environment. Optoelectronics is used for dashboard instrumentation panels, particularly using electroluminescent or plasma discharge panels. In the future the use of liquid crystal displays may increase. Route guidance systems and more sophisticated diagnostic systems will increase the need for more displays, though multiple use of a single display panel is likely. Route guidance systems may also stimulate the need for map storage using optical storage systems and in-car compact disc players are likely to become popular. The increasing use of electronic control systems, sensors and actuators favours multiplexed communication of information around the vehicle using a few wires instead of large, heavy wiring harnesses. As faster data rates are needed, the preferred solution will be to use optical fibres instead of copper wires which are also less susceptible to electromagnetic interference and hence more reliable Optical sensors may be used where electronic sensors are not available, eg for combustion sensors, or where improved accuracy is thus obtainable. Rugged, low cost optical fibres and connectors are crucial to the penetration of these systems.

An estimate of the world market for automotive optoelectronics based on the figures for electronics suggests a figure of a billion pounds per annum by 1990.

3.0.2.2 *Aerospace*

The aerospace market can be characterised by the need for high reliability and the consequent long development times. Optoelectronics has not yet had a significant impact on the market, except for cockpit displays and thermal imaging. In the next decade this situation will be dramatically changed. Demand for flat panel colour displays and head-up displays will be significant for military and civil aircraft. Navigation aids, based on either ring laser gyroscopes (for high accuracy) or optical fibre gyroscopes (for low cost) will become important. Optical fibre communication around the airframe is under active development to reduce weight and give increased immunity to electromagnetic interference. Optical sensors will then be needed around the airframe. Missile guidance using trailing optical fibres is well developed and could be a significant market for optoelectronics. Faster radar signal processing using optoelectronic or optical processing systems will become more important for target recognition, and optical techniques provide the ideal solution for direct satellite to satellite communication.

It is difficult to separate the total aerospace market for optoelectronics from military market estimates. Production figures estimated for the latter half of the next decade are of 250,000 guided missiles and 14000 aircraft (including civil).

3.0.2.3 *Medical*

The major and most familiar use of optoelectronics in medicine is optical fibre endoscopes and semiconductor imaging sensors used for internal examination. High power lasers for surgical use are an important application and their exploitation is largely in the hands of small specialist firms. Optical sensors have the attraction of added safety for the patient - as no electrical contact need be made to the body and they can be more easily sterilised. Thermal imaging is being investigated for diagnosis purposes.

Although the optoelectronic share of the medical equipment market was estimated to be only £60m worldwide in 1986, there are significant opportunities for growth and the UK may be well placed to exploit niche areas of this market.

3.0.3 Other Markets

3.0.3.1 *Materials Processing*

The use of lasers for welding, soldering, surface working, cutting, hole drilling, marking and scribing is the major use of optoelectronics in this area.

The laser equipment market size was about £66m worldwide in 1986 - growing at 20% per annum within the total market for systems valued at over £200M.

3.0.3.2 *Process control*

In process control, the opportunities for optoelectronics lie within the sensing and data communication areas. Developments have been largely as a result of spin off from the military and communications markets and this is likely to continue. To increase the rate at which this occurs - and to ensure a UK position - this area would be an ideal one for a demonstrator project.

The total process control market is currently about £8.6 billion of which the optoelectronic content is less than 0.3% (£26M). In ten years time, the optoelectronics penetration is likely to grow to 1-2% (£90M - £200M).

3.0.3.3 *Safety and security*

Again this market draws heavily upon developments from other markets, notably in the areas of sensors, optical fibre communications and imaging, where the passive nature of optical devices is important.

The total UK market for safety and security systems is estimated to be currently worth about £1.5 billion per annum, with optoelectronic devices forming an integral part of the majority of systems.

3.0.3.4 *Energy*

The only major use of optoelectronics not covered elsewhere is in solar cells. The major current applications are for portable equipment, locations where it is uneconomic to make a connection to a grid-based electricity supply and as a power source in less developed countries.

For obvious reasons, there is not a large market in the UK, but the UK is well placed to access the world market which is about £300m. New market opportunities are heavily dependent on oil prices but the market size in the year 2000 is estimated to be £3000m.

3.0.4 Matrix of markets and technologies

Figure 7 shows a matrix summary of some important aspects of the discussion of both markets and technologies presented in this report. The markets are presented in decreasing order of size down the left-hand side and the technologies are presented in the order in which they are described in Section 4. Information, on both the importance of each technology to each market and the UK position in research and development expertise in each technology for each market, was derived from the perceptions and experiences of the members of the working group, supplemented by the evidence obtained during the course of their study. The absence of any symbol in the matrix indicates a very low or zero " score ".

The best position for the UK would be to have excellent R&D expertise wherever a technology had any importance to a market! This cannot realistically be achieved; but a reasonable aim is to have excellent R&D expertise wherever the technology is very important to a large market. It is clear from the matrix that the UK is very well placed within the military market. The matrix says nothing about the UK's ability to exploit this expertise - merely that the potential exists. Generally the position is also promising in the communications and information systems markets. The UK is less well placed in the consumer market, but the number of relevant technologies is fewer here.

The most depressing situation is where the technology has great importance to many markets but the UK lacks significant R&D expertise. The only very significant example of this, indicated by this matrix analysis, is in the field of optical storage of information. It is clear that the UK is not currently well placed to benefit from the forecast increase in high capacity optical storage systems and a strategic initiative to stimulate the UK is necessary.

The aerospace sector in particular may be an area where the UK can build on its strengths in other markets to develop a technical lead. This is undoubtedly also true of the process control and safety and security markets to a smaller extent.

In general the picture painted by this analysis is that optoelectronics does indeed have a very wide range of applications and that, at present, the UK is not poorly placed with regard to its existing R&D expertise - the exception being optical storage. However, many of the technical leads that were established by the UK have been eroded by intense competition from the US and Japan. It is therefore imperative that research and development is stepped up to maintain and extend these UK skills and action taken by industry to exploit them effectively.

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MATRIX OF MARKETS AND TECHNOLOGIES

MARKETS \ TECHNOLOGIES	Materials	Transmission and switching systems	Components for communication systems	Optical information processing	Optical storage of information	Displays	Imaging	Sensors	Lasers
COMMUNICATIONS	●●● 000	●●● 000	●●● 000	●●● 000	●	●● 00	● 0		●● 00
INFORMATION SYSTEMS	●● 000	●● 00	●● 000	●●● 000	●●● 0	●●● 000	●● 00		● 00
CONSUMER	●● 00		0		●●●	●●● 00	●●	●	
MILITARY	●●● 000	●●● 000	●●● 000	●●● 000	●●● 0	●●● 000	●●● 000	●●● 000	●●● 000
AUTOMOTIVE	●● 00	● 00	●● 0		●	●●● 00	0	●● 00	
AEROSPACE	●● 00	●● 000	●● 00	●● 00	●●	●●● 00	●● 00	●● 00	● 0
MEDICAL	●● 000	0	● 00	● 0	●●●	●● 00	●● 000	●●● 00	●●● 00
Materials processing	●● 00								●●● 00
Process control	●● 00	●● 00	●● 00	0	●	●● 0	●● 00	●● 0	● 0
Safety and security	●● 00	●● 00	●● 00	0	●	● 0	●●● 000	●● 0	
Energy	●●● 00								● 0

Importance of technology to market : ●●● High ; ●● Medium ; ● Low

Quality of UK R + D expertise : 000 High ; 00 Medium ; 0 Low

Figure 7

3.1 Communications

Although the benefits of broadband transmission are well known in information technology circles, it is worth noting those benefits which can be obtained by enhancement of existing electrical transmission techniques and those which are feasible only with fibre optics. A single fibre optic line can carry a whole range of services with maximum efficiency. These services include telex, facsimile, data transfer, high quality sound, TV library and information services. To this end all the world's major carriers have embarked on large programmes to upgrade their networks with optical fibre based trunk systems. These systems will extend from the trunk network first to major businesses and finally to domestic consumers. The uncertainties relate to the timing of the introduction of new services, the standards to which they are to be implemented, the legislation which governs the relation between the providers of the network (common carriers) and the customers, and the competition between optical fibre and satellite transmission. Furthermore, the weight of existing investment in metal lines leads to inertia, and radical departures from existing practice do not always provide equivalent benefits until they are adopted by a significant part of the customer base.

These problems have an international dimension: it is desirable to extend the integrated services over a worldwide network as telephony is today, not only to increase the benefits but to provide markets on a scale which gives a satisfactory return on investment. In contrast to the conservatism of most network operators, Japan has declared its intention to demonstrate the advantages of integrated broadband networks, creating a demand for services, which, like video tape recorders in this decade, cannot for long be frustrated.

In the local exchange network or 'subscriber loop', most of the services required by a single business user can be carried by metal wires. A pair of wires can carry telex or low speed facsimile when not used for a single telephone conversation. If optical fibre (or coaxial cable) is used, new services can be offered in high speed facsimile, medium speed data and high quality sound. Such services can be offered separately, or the fibre can carry many telephone conversations (channels). More powerfully both telephony and other services can be offered in an integrated services digital network ISDN.

At present it is usual to see thirty telephone channels, or their equivalent in data capacity in such low capacity short haul systems. Provisions of these new services will create demands for greater capacity in long-haul transmission, though the shape of that demand will depend on the physical configuration of exchanges - a dense net in Western Europe, a linear net in Japan and dense networks separated by very long-haul lines in the USA.

The growth of such services may be expected to occur in an evolutionary way, accelerated by increased use of computer aided design, by personal computers in home and office and by high density of information possible on relatively low cost optical disc storage. These in turn can create a demand for high speed data (or high volume file transfer) into the local exchange. As well as banking, insurance, distributive and manufacturing industry, national and local government will be large users of these data highways in social security, hospitals, inland revenue, education, police and defence.

On the other hand there is an existing demand for FM stereo radio and television currently satisfied by direct terrestrial broadcasting, satellite transmission, and cable TV (CATV) including optical fibre delivery systems. Conventional broadcasting is approaching saturation due to the physical constraints of the available bandwidth. At the same time, the economics of satellite TV broadcast direct to the consumer (DBS) have become less attractive even in countries like the USA where the population density is relatively low. Coaxial cable TV has the advantage that the analogue video signal can readily be transmitted directly without digital encoding. An attractive compromise solution is to transmit the signal digitally over longer distances in optical fibre and use coaxial transmission to the consumer. As costs decrease, the optical fibres can then be taken to all end users.

It is considered that four simultaneous TV channels will be required by the customer selected from a larger number of available channels. High definition television (HDTV) may be added when available and the wide penetration of broadband optical fibre into the network will allow the growth of other services. Schools, colleges and universitites could access libraries of educational video discs or tapes, not just on the basis of a local area network but nationally. Security and traffic surveillance could also economically use public networks. A great stimulus would be given to publishing through the medium of optical disc and tape, and to the use of high quality displays and printers for generating high quality hard copy. It is even sometimes claimed that newspapers will be economically distributed by this method.

The growth of these broadband services to the consumer will lead in turn to a demand for more channel capacity elsewhere in the trunk and junction networks, from the suppliers of services and from the main business users. Such bandwidth in turn will enable greater use to be made of other services, e.g. teleconferencing.

Finally, the increased channel capacity in the junction network and widespread penetration of broadband networks into the consumer network facilitates the development of a video phone service. Such a service would demand wide band transmission from, as well as to, the consumer, particularly from the domestic consumer. The demand for such a service should be anticipated when the broadband services are first introduced to the ordinary consumer for reception, so that the infrastructure is capable of subsequent enhancement.

The overall process of rewiring a country for fibreoptics is extremely complex and needs vision on the part of the network operators and the optoelectronic industry. That vision must be under the jurisdiction of a suitable technical and legal framework to define the role of the network operators, to protect copyright and to regulate relations with other countries.

3.1.1 UK market

The vision of the General Post Office, and since 1981 British Telecom, has been largely responsible for the currently satisfactory situation in fibreoptic telecommunications and the UK's position as fourth or fifth in the world league. Recently that enterprise has been complemented through investment by Mercury Communications.

The strength of the UK industry is mainly due to BT as a customer promoting substantial investments in research, development and production by UK firms, building in part on research foundations originally stimulated by the Ministry of Defence. By 1986, half the trunk network was already digital and all of it will be by 1989, such a network is, of course, suitable for accurate transmission of data and undistorted speech. By 1988, sixty main switching stations will be connected with fibreoptics, half of which were already connected by the end of 1986.

These stations will bring digital communications within 20 or 30Km of the majority of subscribers; 95,000Km of optical fibre was already installed by the end of 1985. The standard transmission rate is equivalent to one TV channel (or 2200 voice channels, or 140Mbit/s), but it is expected that in the next few years domestic demand will rise to 500 terminaation units per annum at this capacity and 60 termination units per annum at 4 TV channels capacity or 565Mbit/s. BT may also need some 2400Mbit/s systems and has installed an experimental system. Mercury currently also uses 140 and 565Mbit/s systems.

Optical reliability of fibre systems has been generally good, although remedial work required on installation has varied widely. In contrast, the reliability of the electronic portion was poor on early equipment because of high component counts due to relatively low levels of custom integration.

In the local network, multimode systems currently operate at 2, 8 and 34 Mbits/s, but all systems will be single mode in future. Some 14,000 short haul links will be required per annum by BT, particularly for the City of London network. Mercury has installed local loop 2Mbits/s optical fibre systems in the City and plans extensions there and elsewhere.

Outside the telecommunications network at the moment, cable TV uses fibreoptics in three cities. Otherwise there are comparatively few local (or metropolitan) area networks at the moment. Rail, water supply, electricity supply, petroleum, hospitals and defence provide current and future markets for local area fibreoptic networks which may be connected into the public networks.

Wideband submarine fibreoptic cables have been laid by STC from the UK to the Isle of Wight and Belgium and have been ordered from STC for a link to Denmark and for part of the next transatlantic cable TAT8. Cable and Wireless have also ordered a private transatlantic cable from STC, and have adopted an aggressive international stance as part of their attempt to secure major submarine cable business worldwide, most notably in the pacific. Previous Cable and Wireless success has benefited STC who are a leading world supplier of submarine systems. The UK therefore has a strong position.

The UK is making the investments necessary to meet these foreseen demands. There are four indigenous optical fibre manufacturers (Optical Fibres, GEC, Pirelli, STC), six cable makers, three major system suppliers (GEC, STC, Plessey), two major optoelectronic component suppliers (STC, Plessey) and many minor ones. The domestic market so far described does not alone justify the investment being made: its justification rests on greater penetration into the local network, in particular to the domestic consumer, and in expansion into Europe and elsewhere. Of the 27 million telephones in the UK the vast majority belong to the 250,000 businesses using more than a single line, of which some 150,000 can be regarded as key users. Of these in turn, 65,000 can be categorised as large businesses. The only service of note common to both sectors is the public switched telephone network (PSTN). Despite the much greater number of lines in the domestic sector, the revenue from telephony is about the same in both sectors at approximately £2000M as line usage in the business sector is six times higher. In the short term increased revenue is seen as coming from a relatively small deployment of capital assets in the business sector where a 64Kbits/s line for digital voice transmission line can be matched by existing telex, facsimile and data transmission services at a similar or lower rate, moving to data links at up to 2Mbits/s for larger business users. These provide the natural markets for optical fibre systems in the short to medium term.

In the longer term it can be envisaged that over ten years, perhaps half of the thirty million or so links would be connected to an optical fibre based broadband communications network offering TV and many other services. If the capital cost were brought down to £200 per connection, this would create a market of £300M per annum. Some indication that such a cost would be acceptable to the consumer may be gained by comparing it with the current UK market of £400M per annum for video tapes.

3.1.2 European markets

The 350 million people in the western block in Europe might constitute a natural market for the UK in optoelectronics were it not for the protectionist policies of the network operators, aided by different technical standards. The maturity of the UK market compared to most of Europe leads to a lower 5-year forecast of average annual growth rate (24%) compared with many of the major European markets - Germany 40%, France 31%, Italy 23%, Spain 38%.

Telecommunications applications dominate the market for optoelectronics in Europe, accounting for three quarters of the market in the UK. Particularly rapid growth is shown by West Germany because of plans to introduce optical fibre widely into the local network or 'subscriber loop'. France has developed urban networks but has not yet begun its trunk networks since it has only relatively recently upgraded it to coaxial cable. A market corresponding to the one described in the UK for ordinary subscribers in the local network, wherein half of the 140 million subscribers in Western Europe were connected to a broadband network over ten years at a cost of £200/line, would be worth £1400M per annum.

UK and European companies are cooperating in the EC RACE project and on certain important component technologies in the ESPRIT programmes. Although relevant and useful, the pace of the RACE project does not match the likely timetable for the introduction of integrated broadband services in fibreoptics based on investment in Japan, the USA and elsewhere. The cooperation is being supplemented by individual agreements between companies, but RACE remains a valuable forum for the generation of European standards and the integration of the market.

3.1.3 USA market

The USA market in fibreoptic telecommunication, worth $500M in 1985, is expected to grow to $600M in 1990. Currently, long distance high bandwidth links form the largest segment of this, the largest market in the world; but feeder lines in cities and local area networks are important. While AT&T businesses have installed their own fibreoptic system, other network operators have bought some systems from abroad, a few having been bought from the UK and France. However, some 40% of optoelectronic components are said to be brought from just two Japanese firms.

Outside the trunk network, its feeders and larger offices, a number of factors suggest that the USA market for optoelectronics in telecommunications will be conservative. The network is by no means all digital and the long distances between houses has led to an investment of 827 million miles of copper wires. Furthermore US cities are extensively wired in coaxial cable for CATV, sometimes with large capacity systems quite recently installed. US telecommunications standards are different from those in the UK and companies will need to make special investments to enter this market. Ultimately its size and openness make it attractive.

3.1.4 Japan

Data produced by OITDA make Japanese production figures easily accessible. In 1985, of £3,840M (864,000 million Yen) total production in optoelectronics, 40% or £1,524M lay in the field of communications. Internal growth of 37% resulted in part from NTT's investment in its 400MBits/s trunk network between 1985 and 1986. NTT have stimulated the industry through their own research and procurement. Local area networks have been extensively introduced into factories and offices, and four rival national network operators to NTT are emerging, based for example on the railway system.

The national consensus on the role of optoelectronics, like that on VLSI and computing, has led to the emergence of a very strong industry. National plans, industrial commitment and long term planning, public purchase and low interest rates all play their part in creating an industry very competent in every major aspect of optoelectronics in telecommunications - integrated optics, integrated optoelectronics, optical fibres, lasers, detectors, connectors and system design. Their excellence, combined with the difficulty of penetrating the Japanese market means there will only be minor opportunities for UK firms there. On the other hand, their production resources will be directed at retaining a large share of the rapidly developing world market, based on a well demonstrated capability in their own home market. Their greatest opportunities lie in the subscriber loop or local exchange area where low cost production can make systems economically attractive to the subscriber, while deeper within the system wideband links up to 9.6Gbits/s provide the bandwidth necessary to serve the subscribers' needs. Immensely valuable though all these markets will be in their own right, the transmission market could open the door in turn to sales in public switching, videophone and other displays, with optical information systems of still greater value.

3.1.5 Discussion

Although the UK has a substantial investment in optoelectronics for telecommunciations from research to production and is in the midst of major installations by the network operators, the prospects are cloudy in the longer term. A major obstacle is the timing and legal framework for optical communications in the local network, as it penetrates to serving a majority of subscribers. It is commonly agreed that fibreoptics will represent the preferred solution in an integrated broadband communications network (IBCN).

Satellite transmission will be integrated into such a network and for a time copper pairs and coaxial cable will coexist with optical fibre. Some nations, notably Germany and Denmark, are committed to serious demonstrations of optical fibre networks and it can be expected that large scale optical fibre installation in the subscriber loop will begin in the early nineties.

Fibre optics offers the potential for the integration of all the required services. Present legislation requires cable consortia to include BT or Mercury if they wish to convey telephony services, and to apply for a license in each separate area. The effect is to divorce TV from other services and to require that every subscriber pay indirectly for the cost of running interconnections to his home or office on two independent networks. Under these circumstances, neither the TV networks nor the telephone network can have the breadth of vision or the cohesive market to offer the range of services that might be available in other countries.

The Peacock Committee on Financing of the BBC (1) recommended that 'National telecommunications systems (e.g. British Telecom, Mercury and any subsequent entrants) should be permitted to act as common carriers with a view to the provision of a full range of service, including television programmes'. Legislation involving this recommendation would also imply a divorce between the provider of the service itself (TV, radio, data etc.) and the means by which it is brought to the consumer. Such an arrangement provides for maximum competition in TV, publishing, financial and data processing services, with the best chance of their penetration to the whole community.

However, the network operators are constrained by commercial considerations. Short term pressures may preclude BT from making a significant early investment in establishing a broadband local network, resulting in R&D proceeding more rapidly overseas, building up the capability of foreign industry. When BT and Mercury do enter the procurement market, foreign companies may well by then have proven systems to offer in competition to untried British offerings. The Government should therefore encourage the network operators to set up a number of broadband local networks as large scale demonstrators to develop a UK indigenous capability. Public purchase of installations for use by Government and local authorities, schools, colleges, the health service and police could provide high profile sites for such demonstrators.

The demonstrators although offering real services, could be regarded as part of large scale research on systems and engineered to illustrate advanced technical features that will form part of future systems. Thus single mode fibre should be used to ensure maximum bandwidth and the possibility of incorporation of coherent optical frequency-multiplexed systems, rather than direct detection. As well as providing valuable technical experience, the demonstrators would enable research into the factors affecting the likely level of demand for broadband services. The patterns of use by the various groups connected to the system - domestic consumers, large and small businesses, etc - could be assessed under commercial conditions, to avoid costly and unproductive errors when eventually much larger areas are connected to fibeoptic cable systems.

Up-grading of the system should be envisaged from the outset so that it could be a focus for work done under the JOERS and RACE programmes. In view of the national purchasing policies operating in most of Europe, access to the demonstrator should be negotiated on the basis of reciprocal agreements for nations giving favourable access to UK firms on their own demonstrator schemes. The demonstrators would form a showcase for UK technology as well as a guide to UK network operators in their future purchases.

In 1980, the UK had a balance of payments surplus in telecommunications equipment of approximately £25m. By 1985, this had swung to £70m in the red on a trade volume of £435m, growing to an estimated deficit of £180m in 1987. Industrial production investment must therefore be planned to capture a significant fraction of the world market, not just the UK market, if it is to survive long term. This implies the forming of strategic alliances with companies located in the major world markets - Europe, North America, & Far East in order to obtain direct access.

The only largely untapped major world markets are China, India and Russia. UK companies are active in China but their profile is lower than that of US and Japanese companies. Given greater understanding between Russia and the USA, major shifts could occur quite rapidly: we can be certain that USA and Japanese companies will quickly fill any gaps. The UK should be building contacts now.

3.2 Information systems

Optoelectronics is already finding applications within the informations sytems market, the largest segment of which is the computer market, as relatively self-contained sub-assemblies, eg liquid crystal displays on portable computers, optical storage devices. In such cases, the manner of operation remains unchanged and the optoelectronic devices are integrated within a conventional electronic computer.

More fundamental changes are taking place however, such as the use of fibreoptic backplane buses in central processors, for example in the ICL series 3900 mainframes, to link the various parts together to increase speed of operation and reduce electrical interference problems. The use of optical interconnects is certain to increase and move down the scale from interconnecting peripherals, to sub-systems, to boards and then the chips themselves. Ultimately, as discussed in section 3.6 on optical information processing, the whole operation can be conceived as taking place using light in place of electricity. The essential question in addressing the market opportunities for optoelectronics in computing is the timeframe in which these developments are set.

3.2.1 Fibreoptic networks

Fibreoptic local area networks (LANs) already offer a competitive alternative to metal wires for long unrepeatered sections of a network, installations in hostile or electrically noisy environments, and for improved security against eavesdropping. They offer much higher bandwidth for baseband or broadband systems becoming economically most effective at data rates in excess of 100Mbits/s. However, optical fibre is more difficult to terminate and tap into than metal wires which can be a disadvantage in terms of flexibility, but development of low cost connectors and termination techniques in the telecommunications industry will most probably be able to be spun off into the computer industry to overcome this difficulty.

Table 3.2.1 gives estimates for the size of the market and its predicted pattern of growth. This reflects the anticipated growth of computer applications, but more especially their increasing penetration into the office environment and the move towards more distributed architectures making increasing use of local processing and storage.

TABLE 3.2.1

MARKETS FOR FIBREOPTIC LOCAL AREA NETWORKS

	USA	JAPAN	EUROPE
1981			
Commercial applications	85%	80%	78%
Office applications	15%	20%	22%
TOTAL:	$4.6M	$1.6M	$1.5M
1990			
Commercial applications	71%	73%	66%
Office applications	29%	27%	34%
TOTAL:	$20M	$45M	$38M

3.2.3 Optical interconnects

The arbitrary distinction drawn between fibreoptic networks and optical interconnects is that the former concerns links into the external world whereas the latter deals with internal communication within the central processing unit and its peripherals. For both, but especially in the case of the former category, the existance of widely accepted standards is an essential requirement. An evolving standard which is likely to become dominant and give rise to the necessary chip sets etc is the ANSI FDDI (Fibre Distributed Data Interface) interface.

However, the internal communications between boards, and ultimately between chips is the domain of the computer manufacturers and may not always be separately identifiable. Indeed, connections between chips may not use fibres at all, but lenses or holograms to image sources on one chip onto detectors on another.. With the development of faster electronic technologies such as gallium arsenide and the potential of superconducting ceramic substrates, the need for high speed, parallel and non-interacting data highways will become increasingly vital.

3.2.4 Data storage

Optical data storage is poised for a massive explosion. The technologies are described in section 4.7 'optical storage of information' of which the computing market will be a major beneficiary.

Mainframe computers will make use of optical disc drives of up to 14 inches diameter storing several Gigabytes of data - comfortably able to store the entire output of the best typist from the time she (or he) leaves school until she (or he) retires! Read only, read/write and write-once-read-many-times discs (WORMS) will all have their separate place and be on line simultaneously.

The major growth market however is expected to be the smaller 5.25" and 3.5" drives allied to microcomputers. This is occurring partly as a spin-off from the technology for compact audio disks (CD) which have become popular for high quality music reproduction. Because the audio tracks on CD are stored digitally and read by a laser, the medium is suitable for mass-produced, non-erasable digital data storage. This is known as CD-ROM: Compact Disk - Read Only Memory. Predictions for the growth of CD-ROM are shown in Table 3.2.4.

TABLE 3.2.4

WORLD MARKET FOR CD-ROM PLAYERS

	VOLUME	VALUE
1986	15,000	$9m
1988	275,000	$66m
1990	1,500,000	$203m

(Sources: Dataquest and Financial Times)

Total market estimates for optical discs and their associated drives put current revenues at $500m (1986), rising at a growth rate in excess of 30% to reach almost $13 billion by 1996. At this stage, it is predicted that optical storage media will have secured three-quarters of all the data storage market.

3.2.5 Displays

Displays, by their very nature are optoelectronic. This study however wished to exclude consideration of mature technologies, although it is obvious that for some time to come, even with the wider usage of colour and the advent of large size high definition screens, the cathode ray tube will continue to dominate the market in volume terms.

The technological developments described in 'displays technology' section will find their way into informations systems, but the driving forces may well come upwards from the consumer market or downwards from military requirements.

There is an undoubted requirement in the computer market for greater resolution for graphics and image display, larger area, colour and rapid refresh rates to eliminate flicker, and for large-scale devices for public events, a niche market in which the UK is currently well placed.

Separate identification of the displays sector is difficult and it is dealt with more extensively under the displays technology section. An indication of the total value of this segment of the computing market may be gained from the size of the flat panel display market, which is currently in excess of £1 billion per annum.

3.2.6 Commercial systems

An increasingly significant application of information systems by optoelectronic component value is bar code scanning for stock control and tracking systems in industrial, commercial and retail premises. This is a significant market for sources, detectors and optical components such as lenses, mirrors, prisms and transparent materials. Ironic as it may seem, such mundane markets can sometimes act as the stimulus to more advanced developments, eg in the initial stages of the development of gallium arsenide as an optoelectronic material, its major market was in infra-red detectors for automatic door control mechanisms.

3.2.7 Optical processing

Ultimately, it will be possible to construct a computer system operating entirely on light beams, but whether this will become a practicable and economic alternative to the ubiquitous electronic computer is open to debate. Certainly, within the ten year time horizon of this study, it looks unlikely.

Where there will be inroads is in the use of special purpose dedicated sub-systems - image processing being the obvious example, working entirely optically but outputing data electronically. Areas where the inherent parallelism of light and absence of crosstalk can be exploited will find the first applications. Because this market is so radically different from what has gone before, predicting its potential is extremely difficult.

3.2.8 Printers

Printers for information systems and the publishing industry itself are increasingly using non-impact optoelectronic techniques to replace conventional methods. The worldwide market for laser devices in reprographic equipment was estimated at $60 million in 1986, the value of the total systems into which they are incorporated being $5525 million (Lasers & Applications, January 1986). The value of the market for the total systems is currently doubling every couple of years, but due to falling cost of the optoelectronic components, the value of these constituent parts is only rising at about 15%.

3.2.9 Comments

The introduction of optoelectronics into information systems is likely to follow an evolutionary rather than revolutionary path. Because of the nature of the change, it is likely that those companies participating in this market will be the existing major players rather than new entrants. This underlines the necessity for those UK companies currently involved to maintain a high level of innovation to avoid their products becoming technologically obsolete.

Since only the largest companies can afford to undertake all the necessary R&D themselves, it will be essential for UK companies to collaborate and form alliances with partners having complementary skills in order to survive.

3.3 Consumer

The worldwide market for electronic consumer goods was estimated at £21 billion in 1986 (Industry sources). Optoelectronics will have a major impact on home entertainment and education on which this section will focus. Home computers, telephony and safety and security systems are included under their own separate market headings.

3.3.1 Television

The most common optoelectronic device currently is the ubiquitous television. Virtually every household has one, many having several. The market is currently mainly replacement, with limited scope for expansion except for limited features such as teletext, stero sound and flatter, squarer tubes (FST). The potential for major growth will be generated by the introduction of high definition television (HDTV) broadcasts combined with technical innovation producing large area, flat screen colour displays. Section 4.6 on displays reviews the technological issues, but the timescale for the maturity of this technology will depend on a combination of technical, marketing and political issues, with the subject of standards featuring prominently. Once established, the market in the UK alone will be in the region of 50 million units with a correspondingly large world market.

Solid state video and 'still' picture cameras employing electronic storage will become more prevalent as the cost of the technology falls, but the value of the market will almost certainly remain at least an order of magnitude below that of the mass reproduction devices.

Subsequent developments may yield 3-D television, most probably using holographic techniques, but the introduction for such a radical development which would have major repercussions for the production of programme material is likely to be very much beyond the timescale of this study.

3.3.2 Storage and retrieval systems

The major consumer market growth area for optoelectronic devices is the compact disc (CD) player. Table 3.3.2 illustrates this growth:

Table 3.3.2

GROWTH OF COMPACT DISC PLAYER MARKET

	UK SALES (Thousands)	HOUSEHOLD PENETRATION
1982	5	0%
1983	12	0%
1984	28	0%
1985	125	1%
1986	500	3%
1987 (forecast)	750	5%
1990 (forecast)	650	14%

(Industry sources)

Associated with this is the sales of discs themselves, 140 million worth some £1 billion being sold worldwide in 1986, of which the UK market accounted for 8.4 million (£56.5m). The world market is predicted to grow to £2.2 billion by 1990 as volumes increase rapidly but prices fall.

In contrast, videodiscs have been confined mainly to the professional users, training being the main application where interactive videodiscs are being found increasingly widely used. Early trials underestimated the amount of resources required to produce software of an acceptable standard, but growing experience has shown that the rewards can be worth the investment. The UK market at present is the world's second largest interactive videodisc market with sales currently some 2500 players per annum, but predicted to expand to 20,000 units per annum by 1990.

CD-ROM, described in detail in section 4.5.2 is set for more meteoric growth. Worldwide production is currently 15,000 per annum (1986), predicted to grow to 1.5 million by 1990, when it will be worth $200M. This growth is based partly on the use of CD-ROM as a data storage peripheral for a computer system, but systems are already being demonstrated which combine the functions of CD-ROM and the compact audio disc to produce a multifunction machine capable of storing text, data, video and high quality sound in an interactive mode if required. The phrase compact disc interactive (CD-I) has been coined, but fully developed products are not expected to appear until 1988. Such a system, based on 12cm discs, would not be capable of producing high quality video due to its slow data retrieval rate, but the next step could be a 30cm double sided disc capable of storing all types of information required of a home entertainment and information centre.

3.3.3 Comments

Optoelectronic devices are also incorporated in many other domestic products, mainly as displays in devices such as cookers, washing machines and watches. Totally new application areas can be envisaged, such as home-based local area networks using fibreoptics, but they are likely to be spin-offs from other markets, eg telecommunications, rather than developed specifically for the consumer market.

The consumer products market is characterised by low cost, high volume, short product life, rapid innovation and strong marketing. Over the last decade, the UK has overall been notable for its failures in these areas rather than its successes. However, the fundamental research base exists within the UK to enable success to be achieved given sufficient commitment to the market.

The UK also requires a more positive attitude to marketing and investment to regain market share. A firm foundation would be provided by better market intelligence and information, allied to a co-ordinated approach by UK industry to ensure that weak links in the chain are identified and strengthened. For example, the initial take-up of CD audio players was crucially dependent on the availability of music on compact disc. New standards might be required before a product can achieve widespread success, and this requires co-ordination and action on an international scale. These tasks are carried out successfully in Japan by the OITDA from which the UK could learn some valuable lessons, though this approach should not be considered an infallible solution: one citation would be the failure of the Japanese to standardise their own video tape recorder standards.

There is also the software or data for a given system, for example, the a compact audio disc player is currently about the same cost as twenty discs to play on it. Since most purchasers will buy many more discs than this during the lifetime of the equipment, there is clearly a larger market for the software than the players themselves. Since the UK is traditionally strong in the music business, the importance of a manufacturing position in the technology itself must be kept in perspective in relation to the business opportunities created by the new medium itself.

Similarly for CD-ROM and CD-I, the UK has a history of success in the publishing industry and any deficiency in the performance of our UK manufacturing sector in these technologies should not be permitted to jeopardise the progress of these applications sectors.

A final related point is the requirement when developing modern consumer goods for micromechanical engineering skills to develop the products and production engineering expertise to produce high quality finished goods in sufficient volumes at low cost. For the last decade, Japan has dominated world markets due to its prowess in these skills. UK universities and polytechnics need to ensure that sufficient high calibre engineers are being produced with the necessary expertise in these essential disciplines to meet our national requirements.

3.4 Military

The military market for optoelectronic components and systems in the western world is approximately £2 billion per annum, about half of this being in the USA. The rate of growth is expected to continue at 15-20% per annum in real terms up to 1989. Key current technologies are thermal imagers, image intensifiers and other infra-red sensors, lasers, fibreoptics and displays.

The use of imaging sensors is likely to continue to expand. Autonomous weapons is one major growth market, and this is a major driving force for the current research programmes to produce infra-red staring arrays that are compact, rugged and much cheaper than present thermal imagers. Hand held night sights are another growth area. Widespread use of cheaper optoelectronic sensors may substantially alter defence strategy, for example through smart weapons of many kinds and through enhancing the role and effectiveness of the infantry. Lasers will also continue to be important for defence, for range finding and guidance, and also potentially as weapons.

Fibreoptics will increasingly replace metal cabling for military communications. They will be used in a wide range of applications and cable types including permanently buried cables, underwater cables, cross-country recoverable cables, and local area networks and data highways within command centres, ships, aircraft and other equipments. The military demand for communications is rising rapidly, and the future world market for communications systems exploiting fibreoptics could exceed £1 billion per annum. Behind this spiralling demand lies the rapid pace of modern war, the need to bring much information to bear in order to take decisions very rapidly, the advantage that can be gained from improved surveillance and target acquisition, and from the ability to deliver weapons to exactly the right place at precisely the right time and at longer ranges. Here the ability to progressively extend fibreoptic bandwidths may be important to cope with increasing communications loads. Defence will also continue to be an increasing user of civil telecommunications facilities.

In command, control and intelligence, increasing use is being made of automated data processing and decision support systems. This is likely to expand the military market for data storage including optical memory. Defence is also making increasing use of expert systems and databases for support roles, such as repair, maintenance and logistics. Again optical data storage may find many applications. More generally defence is beset with inordinate amounts of complex information, and much of this is likely to be transferred to optical memory during the next 15 years as increasing use is made of support systems for management, analysis and decision making.

The military research market in optoelectronics is mainly concentrated in imaging and lasers, and this has expanded further due to the Strategic Defence Initiative (SDI) which requires research on very advanced sensors and lasers, including high powered lasers. SDI has also enhanced UK research in digital optical computing; this reflects the enormous real time computing power that is needed in large systems for surveillance, target acquisition and command and control. In the areas of fibreoptics and displays, defence procurement depends primarily on technology developed for the civil markets.

In the UK, MoD is the sole purchaser for the home market, where MoD spends over £8 billion a year on equipments on all kinds, and is the largest single customer of British industry. Further information is included in section 3.6 on aerospace and section 5.5 which describes MoD activities in optoelectronics.

3.5 Automotive Market

The major area of growth in the automotive sector in the last decade and for the next decade is electronics. The application of optoelectronics to vehicles will vary in its impact, and be highly dependent on the relative cost of "conventional" electronics and optoelectronics. Only in isolated cases does optoelectronics offer the sole solution that could not be achieved using conventional electronics, although optical techniques offer distinct advantages in an automobile environment in terms of reduced susceptibility to electrical interference and reduced weight.

The optoelectronic technologies that are closest to the market are displays, fibreoptic interconnections, optical sensors and optical data storage. Future developments are likely to see increasing use of optical sensors and optoelectronic control systems to replace electronic components in existing systems, competing with them in new applications such as active suspension, engine management, traction control, driver information systems, etc. The major growth areas are likely to be safety systems and passenger comfort.

3.5.1 Applications

The increasing amount of information about the vehicle condition being available to the driver has stimulated the development of complex displays using CRT's, vacuum fluorescence, light emitting diode and liquid crystal technologies. The trend to replace mechanical instrumentation will continue. There is interest in the use of head-up displays for ergonomic reasons. The development of car navigation systems will also require displays varying in complexity from direction arrows to map display. The supply of displays for automotive use is currently dominated by the Japanese.

The most likely large scale introduction of fibreoptic technology on vehicles will be for a multiplexed data bus to replace a conventional wiring harness. On top-of-the-range cars with a high electronic content, the wiring loom, particularly to the driver's door, becomes large and heavy, making installation difficult and expensive. Data multiplexing or remote switching can provide the solution to the size problem, but as data rates increase to include engine control data and immunity to electromagnetic interference becomes important, there are cost benefits and size/weight advantages to be gained from using a fibreoptic multiplexed system. Several companies in the UK have demonstrated such systems though none is in production yet. It is suggested that by 1990 US cars will contain a total of $382M worth of fibreoptics, increasing to over $1000M by 1995 (ElectroniCast). It is predicted that 80% of the optical fibre will be silica based, 10% will be plastic clad silica, the rest being plastic fibre. The non-availability of polymer optical fibre capable of withstanding the automotive temperature specification has hindered the introduction of these systems. Again, the Japanese, in the form of Mitsubishi, have recently introduced a polymer fibre capable of withstanding 125 degrees Celcius which should survive in vehicles, except under the bonnet, where operation up to 140 degrees Celcius is required. The UK is well placed in system development but not for component supply.

The automotive industry is amongst the largest users of sensors in terms of volume but demands a very low unit cost. Optical sensors often incorporating fibreoptics, have been designed for the majority of sensing applications on vehicles but few have reached the market place. In general this is due to the higher cost of the optical solution - hindered again by the lack of suitable low cost polymer optical fibre, together with an inherent conservatism in the sector. However, optical sensors offer intrinsic advantages over other types of sensor in certain areas such as measurement of fuel level, oil level, combustion pressure, combustion radiation, etc which may aid acceptance. Combustion radiation measurement is worthy of special note since in this application the sensor measures the light emitted during the burning of the fuel to assist control of engine management, and is an example of a sensor with no electronic equivalent.

The introduction of navigation systems will increase the need for display systems and may also open up new applications to optoelectronics. One company uses optical data storage on compact discs to store entire maps of a country within its navigation system. Currently, magnetic compass or satellite navigation are the most favoured systems for automatic location, though the use of optical fibre gyroscopes has been proposed using relatively cheap optoelectronic components.

Sensors for headway warning (laser radar) and other road traffic control schemes have been demonstrated using optical techniques, though radar or ultrasonic techniques may provide cheaper solutions. The widespread acceptance of these driving aids is by no means certain and thus predictions of market size are difficult. Research in Europe under the PROMETHEUS (Programme for a European Traffic with Highest Efficiency and Unprecedented Safety) scheme is underway.

3.5.2 Market size

In the absence of precise data, the size of the automotive optoelectronics markets is best estimated from the total automotive electronics market. World demand for automobiles is predicted to grow to 47 million units per annum by the year 2000. For the USA, Western Europe and Japan, the predicted electronic content of each vehicle is expected to rise to $2000 by the year 2000 for a vehicle with an average cost of $10,000 (ie 20% of the cost will be electronics), while in the rest of the world the electronic content is likely to be around half this figure.

In order to provide some indication of the optoelectronic content, the market has been broken down into four categories to allow an estimate of the penetration into each category, thus yielding a total figure for optoelectronics. Table 3.5 gives these figures.

TABLE 3.5 AUTOMOTIVE OPTOELECTRONICS MARKET

	Electronic composition		Optoelectronic Content		Optoelectronics Market ($M)	
	1990	2000	1990	2000	1990	2000
Power train controls	45%	27%	2%	10%	275	2225
Vehicle control/ safety/ convenience	20%	27%	5%	10%	305	2225
Driver information	20%	27%	10%	30%	610	6680
Entertainment	15%	19%	5%	20%	230	3130
	100%	100%			1420	14,260

	1990	2000
Total automotive electronics market	$30,700M	$82,300M
Percentage optoelectronics content	5%	18%

(Data derived from various sources)

3.5.3 Comments

The world automotive optoelectronics market is large but the penetration of UK based products is limited because of existing customer bases and the inability to compete with the Japanese on low cost devices. The UK should be capable of manufacturing competitive system using Japanese devices, eg optical fibres and displays, but in this market, it is unlikely that the UK would be able to compete at the device level, except perhaps for niche sensor markets.

3.6 Aerospace

Optoelectronics is an essential technology for a large range of aerospace applications with optoelectronic equipment accounting for an increasing proportion of the value of aerospace systems. The extremes of environmental conditions can be found in aerospace applications and these present challenges for researchers which often promote technological developments of much wider significance.

Aerospace systems are frequently complex and are required to operate safely and cost effectively. New equipment concepts are therefore subjected to economic and technical risk reduction processes which are frequently prolonged, ie it may take anything from 10 to 30 years from concept to entry into service as part of a system; hence research of an innovative nature for aerospace applications is a very high investment risk. This implies the need for good long-term perspective in the selection of those research areas which will enable the development of high value aerospace systems which have a good market potential.

The annual market for aerospace systems towards the latter half of the next decade in the West is estimated to be in the region of a quarter of a million guided missiles and 14,000 aircraft. The greatest volume is in low cost munitions and light aircraft, but if the balance is examined in terms of system value as opposed to quantity, transport and combat aircraft together with long and medium range missiles being dominant. Geographically, the USA is by far the largest single market.

The research motives for the aerospace optoelectronic equipment supplier and the aerospace systems supplier can sometimes lead to divergent conclusions, the former exploring low cost equipment for a lower risk, high volume market whilst the latter seeking high performance for a successful high value system. Other sectors of aerospace, such as spacecraft and the associated ground systems, are additional to the figures quoted.

Over 60% of UK produced aerospace systems are exported, but much electronic and optoelectronic equipment and many components are imported. This implies a situation of some risk, particularly in military markets, unless there is a good indigenous (or as a minimum, European) capability permitting expert specification and acceptance procedures and an ability to establish internal sources should external sources of supply be threatened.

3.6.1 Optoelectronic equipments and subsystems

Currently, optoelectronic devices have only made a small impact on the aerospace market, primarily in displays and thermal imagers. It is estimated that the market for these applications will grow steadily until 1990, increasing exponentially with other applications in the aerospace sector until 2005 by which time all aircraft and guided missiles will include a significant proportion of optoelectronic based equipments and subsystems.

The markets for aircraft and guided missiles are significantly different. Aircraft have an operating design life of 20-30 years whereas a guided missile may be required to have a similar 'storage' life, but only be called on to operate once. Market size may also be a multiple of that derived from the actual number of aircraft or missiles in service at a given time since the former may incorporate duplicated systems for system integrity, and avionics, communications and control systems may be replaced several times during the service life of the vehicles to up-date their capabilities and extend their useful lives.

3.6.1.1. Displays

A revolution is currently under way in the design of cockpits and aircraft flight decks to replace banks of instruments by multipurpose screens to display the necessary information as required. The civil aircraft sector have been in the vanguard of developments and the application to combat aircraft is following rapidly. At present, high resolution cathode ray tubes (CRT) are used, but there is an opportunity for the UK to exploit its excellent R&D in displays to leap-frog existing technology and enter the market with an advanced matrix addressable, high resolution, rugged flat panel colour display.
A number of schemes have been devised for combat aircraft to provide optoelectronic monochrome displays requiring low (battery) power which would enable aircraft to be flown if there is a flight instrumentation failure. Such displays could form a basis for low cost flight instrumentation in light aircraft.

It is also desirable in combat aircraft for the pilot to look through his display at the outside world. The optics of such head-up displays are becoming increasingly demanding, diffractive elements being frequently utilised to provide a wider field of view and lower CRT power. Future developments are likely to include mounting displays directly on the crew where technological innovation in terms of weight and size would be at a premium.

3.6.1.2. Imaging

Imaging technologies as described in section 4.7 will find many applications in aerospace both in civil and military fields, especially thermal techniques for use at night and in cloud. To enhance the capabilities of these systems, lasers may be used for target illumination and identification.

3.6.1.3 Inertial reference sensors

Ring laser gyros are now available for the provision of both rate and navigation information. Their inherent dynamic range should enable the same reference set to act as an inertial navigation platform and an attitude and heading reference system for flight control purposes in certain classes of aircraft. Good reliability seems likely and the market prospects for both high performance and less sophisticated devices are good. Only a short time behind in the development process is the fibreoptic gyro which has good potential for a broad range of lower cost applications.

3.6.1.4 Information transmission

Current US military aircraft equipment standardisation processes indicate a trend towards the future adoption of fibreoptic buses, particularly for high data rates and for video distribution. This trend is supported by the ever increasing growth of processing distributed in centres about airframes and, to a lesser extent, missiles. On the missile side, work has been conducted on the fibreoptic guidance of missiles (trailing fibres) which could indicate one avenue for a larger volume use of fibreoptics in aerospace in the future.

The use of fibreoptic information transmission in aerospace vehicles has the added virtue that it provides a defence against the coupling into the system of a large range of unwanted radio frequencies. However, the technical pressures to adopt fibreoptic transmission systems need to be balanced against the increase in system complexity and the requirements to change installation and maintenance practices. Currently there are only a few isolated examples of their use, although airships are an unusual example of successful application where the benefits accruing from fibreoptic systems have led to their adoption already. However, the advances towards "fly by wire" could accelerate fibreoptic introduction in airframes in which the demands of integrity and safety are high (eg transport aircraft) - especially if there is also available a suitable range of optical transducers for control purposes.

3.6.1.5 Information processing and storage

There is a growing, if longer term demand for more information processing power, particularly for the array processor. The intrinsic parallelism, high bandwidth and speed of optical processing offer an attractive solution. Applications may lie in processing for phased array and conformal radars, analysis of high bandwidth radar data, synthetic aperture radar image formation as well as the processing of conventional imagery such as TV and infra-red. Processing is required are for target lock-and-follow, image enhancement and restoration, pattern recognition and the extraction of signals from noise. Another area where vast processing power is required is for intelligent knowledge based systems, particularly for applications such as sensor data integration and for aiding tactical decisions.

Many mission system processing tasks require a massive information storage capability (eg for map, feature and target data). Ruggedised optical disc storage is a likely solution where high performance is required. Meanwhile, the technology is now emerging for low cost and robust optical storage devices which would be very suitable for mission system pre-flight briefing.

3.6.1.6 Transparent apertures

An area of optoelectronics in aerospace often neglected is the need for material coverings for sensors and crew which are transparent to the spectrum of radiation under consideration. The optical demands on both are becoming more difficult to meet, the former potentially requiring multi-spectral operation while the latter must harmonise with head-up display systems. These optical requirements have to be addressed in the context of difficult structural and thermal environments.

3.6.2 Comments

The UK aerospace industry is currently amongst the leading world suppliers of high performance optoelectronic equipment and systems, together with the products in which the equipment is installed. The prospects for optoelectronics in this market are potentially very good. Aerospace is a growth area and a net exporter for the UK. Optoelectronics is a key technology for this and it is therefore essential to maintain an advanced indigenous capability.

3.7 Medical

Optoelectronics have already found several novel applications in medicine, from the virtually purely opto-mechanical endoscope to the use of a laser as a superfine scalpel. There are many new developments reaching the market, some of which are described briefly below, with many as yet un-thought-of applications waiting to be discovered.

The world market for medical equipment in 1985 was estimated to be $30 billion of which the UK accounted for about 4% - roughly £1 billion, growing at a rate of approximately 5% per annum (ACARD Report 'Medical Equipment'). The optoelectronic proportion has not been reported, but it is likely to be in the region of 3% or so, ie £30M in the UK and $1 billion worldwide, with significant opportunities for optoelectronics to increase its percentage share. The medical equipment market is one in which the UK ought to be successful given the increasingly technical sophistication of the products and the history of excellence in medicine in the UK. In addition; novel, simple and robust optoelectronic systems potentially with disposable probes could create major opportunities for markets in Third World Countries.

The main potential advantages of optoelectronic devices in medicine are the relaxation ofsome of the design constraints essential for safety when using electrical systems, direct biosensor input to optical signal processing and more tolerance of sterilisation procedures. More exotic applications under consideration currently include implanted monitoring instruments and effector devices with percutaneous powering of implanted electronics, and optical control on implanted electronics in response to optoelectronic sensor devices.

The medical equipment market itself is too small to stimulate many technical advances in computing and imaging, but as these developments emerge, the medical profession can capitalise, for example, on improved imaging techniques - ultimately 3-D - for presentation of information; optical processors for parallel processing in real time; and improved computer hardware and software in intelligent knowledge based systems. Significant improvements in health care delivery systems will also be obtained by using transmission and storage techniques pioneered in other markets.

Areas of special interest are dealt with below.

3.7.1 Imaging

Many different methods of non-invasive investigation of internal organs have been developed, each with its own particular strengths. To these has been added thermal imaging which currently depend on cumbersome and expensive liquid cooled devices. Thermoelectrically cooled semiconductor devices or uncooled pyroelectric devices emanating primarily from defence research offer more convenient lower cost solutions which may lead to increasing use of infra-red imaging for the examination of tissues just below the surface of the skin.

X-ray image intensifiers based on vacuum tube electro-optical techniques are well established in medicine. They will undoubtedly continue to play an important part in radiology both for fluoroscopy and digital radiography. Smaller flatter versions of these devices have been developed based on intensifier plate technology. None of these devices are manufactured in the UK. The last company making them (AEI) abandoned the market over 20 years ago. The use of CCD camera tubes with image intensifiers may well lead to slightly more compact systems.

3.7.2 Lasers

Lasers also play a major role in the medical, ophthalmic and therapeutic areas where CO2, Nd:YAG and argon-ion systems are used extensively in surgical and therapeutic procedures.

CO2 lasers are showing promise in general surgery where the 10.6 micron wavelength is ideal for cutting or incisions. They are however basically restricted by cumbersome beam delivery systems to external procedures and are therefore preferred for certain gynaecological, neurosurgical and thoracic procedures. The market could be expanded significantly if a method of transmission along a flexible optical fibre could be achieved.

The Nd:YAG laser with its ability to transmit its 1.06 micron laser beam via fibreoptics can be used with a variety of endoscopic equipments which permit internal medical procedures to be carried out by the surgeon. This wavelength proves ideal for surgery because it induces coagulation which assists in minimising blood loss. New developments using slab techniques to raise the power of this type of laser are increasing the scope of application.

Ophthalmic lasers of the pulsed Nd:YAG and argon-ion type account for approximately 50% of the overall surgical laser market where they are used in a variety of procedures. The argon-ion laser is in addition used in dermatology applications, but the market is almost saturated and there is no UK manufacturer of a medical unit.

In the diagnostic field ion lasers are also finding applications in cell sorting and flow cytometry, while the low cost helium-neon system is still preferred in patient positioning systems, and in aiming beams for the larger CO2 and Nd:YAG equipments.

Excimer and metal vapour lasers are finding applications in medicine. New frontiers in the treatment of some cancers is one exciting possibility where metal vapour lasers could be utilised to trigger a photosensitive drug. Hemataporophoryn derivatives (HPD) are at present being researched for this purpose. Ultra-violet excimer lasers are being developed for eye surgery with early experiments under way to correct myopia by skimming off a minute area from the front of the cornea.

Other prospects in the medical market lie in the fields of laser induced chemistry and diagnostics.

3.7.3 Sensors

Optoelectronic sensors are already finding many potentially attractive applications, for example in measuring blood oxygen concentration levels. In some cases, non-invasive techniques can be used to replace invasive methods whilst in others, immediate results can be obtained by embedding an optical fibre in a catheter, replacing previous surgical practice of removing a specimen of tissue for analysis in a laboratory. By using fabrication techniques such as Langmuir-Blodgett films; extremely selective, sensitive and responsive devices can be developed at relatively low cost, specifically targeted at given parameters.

3.7.4 Automated microsopy

Considerable progress has been made recently in the development of automated microscopic systems to scan cells on a microscope slide and analyse the optical images using a computer. This is of considerable importance for cervical cytology and karyotyping. Special linear array detectors, probably relying on CCD technology to provide increased resolution, need to be developed but due to the relatively small size of the market, the development cost of would need to be shared with other applications - a particular opportunity for spin off from a defence project.

3.7.5 Comments

The Medical Equipment market offers sizable opportunities which the UK is well placed and qualified to exploit. This was recognised by a previous ACARD report 'Medical Equipment', published in July 1986. The report urged the Departments of Health and Social Security and Trade and Industry to continue their efforts to stimulate greater success by the UK medical equipment industry in home and overseas markets by the rapid adoption of optoelectronic techniques in their products.

There is a need for imaginative and far-sighted initiatives which will stimulate the UK supply industry and position it for launching a major export drive. DHSS and DTI would be the spearheads, for example to mount an initiative with UK laser companies, specifically including small and medium size enterprises to increase the penetration of laser eroders into dental surgeries. Although there is already a French/German initiative under EUREKA which has already developed a commercial product and is successfully selling in Europe and exporting to Japan, the market is sufficiently large to stand more competitors. The report by the IT86 Committee also recognised the potential of the medical sector providing an illustration in one of the eight exemplar application projects which described a project for clinical data and process models for the development of health care.

In addition, a considerable amount of work has been done in the USA in laser surgery and laser nursing, where there is a strong move towards treating patients on an 'out patient basis', thus releasing valuable 'bed space'. Indications are that savings in the overall cost of patient care can be as high as 35% in certain areas and patient stay reduced in somecases by 32%. These are averages based on a number of medical procedures and applications.

3.8 Materials processing

The rapid growth of this market sector can be seen in the worldwide sales figures for the use of lasers in materials processing (the main application of optoelectronics in materials processing) which increased from \$69M in 1984 to \$105M in 1986 (Lasers & Applications - January 1986), showing a sustained growth rate in the region of 20%. These figures take into consideration laser equipments only and not the related systems which make the laser into a material processing tool: the added value derived from system sales can offer a multiple of three times the value of the inherent laser technology, the same source reporting total system values of \$233M in 1984 growing to \$343M in 1986.

Similar figures apply in the medical market, implying that the system multiple is increased to a factor of four. This subject is dealt with in more detail in the section on the medical market.

Carbon dioxide (CO2) lasers dominate the industrial materials processing market with Nd:YAG (Neodymium: Yttrium Aluminium Garnet) accounting for the major part of the remaining 33% of the market. In the medical market CO2, Nd:YAG, argon-ion, and dye lasers find applications.

3.8.1 Industrial processing

Lasers can carry out operations in welding, soldering, surface working, cutting, hole drilling, marking and scribing etc. where marked reduction in cost and increased productivity can be clearly identified.

CO2 lasers account for the largest proportion of sales followed by Nd:YAG and Nd:Glass equipments. CO2 lasers operating at 10.6 micron have power levels ranging from 1-10 watts to the larger systems capable of delivering many kilowatts of power.

Nd:YAG lasers operating at a wavelength of 1.06 microns can be operated continuously with powers from around four watts to several hundred watts. It is most effective however when operated in a pulsed mode with powers in the 50-60 watt region.

Excellent examples of lasers in materials processing can be seen in the USA, Japanese, French, German and UK automotive industries where CO2 lasers in the 6-9 kilowatt range are used on the production line for welding and in the semiconductor and electronics industries where CO2 and Nd:YAG systems are used in a variety of applications from annealing and scribing of semiconductor substrates to welding of component containers (relay cases etc).

The Nd:YAG systems have one significant advantage over the CO2 systems in some applications, particularly in confined spaces, in that the laser beam can be usefully piped around the work space (or the patient, in medical applications) by using fibreoptics. The CO2 system which utilises mirrors and conduit to pipe light around the whole area may result in the system lacking the flexibility of the Nd:YAG approach. Lasers have advantages in no tool contact, (no tool force or wear) and minimal heat affecting zone, but yhere may are disadvantages in terms of cost and safety.

Typical applications for lasers can be found in areas such as welding of disimilar metals e.g. iconel to copper, tungsten to stainless steel and in the working of magnetic materials. Welding using 'keyholing' and 'skid' techniques produce results superior to the traditional methods.

In drilling applications high aspect ratio holes can be drilled with high precision and repeatability as in aircraft engine turbine blades. Low aspect ratio holes can be cut by a trepanning technique using an off axis rotating lens arrangement.

In cutting applications narrow 'kerf' can be achieved (typically 1 mm or less) with good smooth edges and lack of dross or molten material.

Lasers are readily adapted to existing automated systems and currently there is a great interest in the marriage of lasers to robots. Many examples of such an arrangement are found in the automotive industry. Although the European market for such machines is growing rapidly the Japanese equipments dominate this market areas with some 20 competitive companies in Japan competing with only 3 or 4 USA based competitors in a market which is virtually worldwide. No serious competition has arisen from Europe as yet.

3.8.2 Future developments

A bright future is consistently forecast for laser equipments and laser based systems, and substantial improvements in CO2 systems should see higher powers being available, while improvements in optics and beam steering devices will allow the systems to address a greater number of applications.

The Nd:YAG laser too will be capable of generating higher powers and already considerable development has been devoted to slab laser techniques for this purpose. In addition, the excimer type laser will find many applications in material processing as reliability improves.

3.8.3 Comments

Generally speaking the use of lasers to replace traditional techniques has now been widely accepted although in the early phases of introduction considerable opposition was experienced from operators mainly on the grounds of eye safety. The car industry in particular experienced difficulty in introducing lasers to their assembly shops. However suitable educational programmes and training in safety requirements has seen this opposition effectively removed from most areas. The general public also has a greater awareness of the role the laser plays in everyday life, for example, medical treatments and in supermarket 'point of sales' equipments.

Cost savings and productivity increases vary in industrial processing, depending on the application but figures of between 18% and 32% have been recorded in both areas.

Finally, it is important to note that market growth rates of 20% and more are being consistently sustained and that the biggest markets are in system sales. Owning the technology is important but does not have the major market impact.

3.9 Process Control

Optoelectronic products developed primarily for the traditional purchasers of process control equipment also have applications in other manufacturing and service industries including automotive, agriculture, laboratory and scientific, medical, aeronautic, defence and domestic supply.

Optoelectronics used in process control include optical components, sources, detectors, display devices and modulators. Sensors are normally required for the measurement of pressure, flow, level, temperature and analytical quantities together with an assortment of other parameters such as viscosity, humidity, speed, displacement, acceleration, density, colour etc. Interfacing devices are required for opto-electric, electro-optic, pneumatic-optic, opto-pneumatic and opto-fluidic conversion, plus data transmission and communication systems.

The industry requires sensors and systems which are cheap to produce, reliable, interchangeable, robust, modular, simple to install, have low maintenance requirements, better performance (range, accuracy, stability, safety, speed of response) than existing components, incorporate intelligence, self diagnostics and self calibration, meet standard specifications.

3.9.1 Future opportunities

Within the next decade, the more obvious opportunities for optoelectronics will occur in the field of sensors and data transmission. Progress to date indicates that fibreoptic sensors may be no cheaper than their electronic conterparts and their signal processing could be more complicated and expensive. In addition, multiplexing of passive fibreoptic sensors is not as simple as for electronic sensors. Optoelectronic systems will therefore have to demonstrate distinct advantages over other techniques before they make a significant impact. Also, for system compatibility, it is desirable that all the sensors should have technical similarity in their outputs, but it could be many years before fibreoptic sensors are available commercially to measure all the required process variables.

Optoelectronic devices will also be at the forefront of developments to improve the utility of industrial automation and robot systems by providing a limited vision capability. This encompasses state of the art applications of sources, detectors, display and processing technology. The other major industrial application is metrology, where the fundamental properties of light can be utilised for measuring the primary parameters of time and length, and hence a whole range of derived units. A particular application where the laser has little competition is in alignment techniques. In this market, the use of optoelectronic techniques will frequently provide the edge to enable a product which utilises them to obtain a technological advantage over the competition.

3.9.2 Comments

It is inadvisable to direct all the R&D resources into the development of a parallel system of electro-optic/fibreoptic sensors, actuators and transmission in the hope that they will compete successfully with the well established and accepted electronic systems. It is important to recognise and encourage R&D where electro-optic and fibreoptic techniques are superior to existing techniques. For example, in certain sensor applications (see section 4.8)

Attention should also be given to the development of hybrid optical/electronic systems which combine optical and electronic techniques to gain the best advantages from the combination of both techniques. Japan and the USA are already following this course to realise such a system as an intermediate step to an all optical fibre sensing system, but it is not too late for the UK to catch up. Several UK firms already have an excellent and well established range of sensors which, with the addition of a long life battery, low current electronic circuitry and simple optoelectronic signal conversion can be adapted fairly quickly and easily to hybrid operation. The process control industry can then be offered optoelectronic systems which have technical advantages without heavy cost penalties.

At the present time the world market for sensors for the process control market, (excluding Soviet Bloc and China) is estimated to be $2.8 billion within a total process control market of $13.8 billion. Equipment and systems other than sensors, display devices and communication networks are unlikely to be challenged by optoelectronic developments within the foreseeable future. The process control market for fibreoptic sensors is currently very small, and even in ten years' time may only rise to 1 or 2% of the total equipment value. Effort needs to concentrated on optoelectronic products which are demonstrably superior technically to electronic equivalents so that UK suppliers can obtain advantage over their competitors in major process plant procurement excercises. Thus although in the next decade the process control proportion of the total market for optoelectronics will be small, its use will give suppliers who possess and apply the technology a distinct marketing edge.

3.10 Safety and security systems

The UK market for security systems is currently £750 million and is likely to grow at a rate of 13-14% per annum (Report of the IT86 Committee). The market for safety systems is considered to be approximately of equal value and subject to a similar growth rate, yielding a total UK market for 1986 in the region of £1500 million. Whilst this is relatively small compared to other areas such as telecommunications, it is one in which traditionally the UK has been successful. This may be attributed to the need to tailor each system to the specific installation, the application of specialist technical knowledge at all stages from design to installation, and the natural advantage of being close to the customer and target site.

The main areas of interest to the safety and security market may be summarised as follows:

A. LEDs, lasers and sensor devices used for the detection of movement, vibration, temperature, smoke, gas and flame.

B. Fibreoptics for communications within buildings to take advantage of the low immunity to electromagnetic and electrostatic interference.

C. Imaging using CCDs and arrays of opto-sensitive devices for flame and movement detection, ultimately interfaced to optical signal processing systems.

D. Specialist applications holography for secure authentication.

Optoelectronics has several inherent advantages over other methods of detection and information transmission in this market:

- difficult to tap or bridge optical fibres
- small size and flexibility of fibres simplifies installation
- direct detection of parameters by optical devices using invisible radiation
- fibreoptic sensors capable of detection throughout their entire length
- immunity of systems to electromagnetic and electrostatic interference
- low energy levels for use in hazardous environments

A number of areas of particular interest are described below.

3.10.1 Sensors

The most common type of detector in this market is the passive infra-red detector, which senses the body heat from an intruder and goes into alarm when a rapid increase above a predetermined threshold is observed. A similar device serves as a fire detector by sensing the build up of infra-red radiation from a growing fire. Active infra-red detectors are employed either as perimeter protection systems around important buildings, or more commonly as smoke detectors in fire protection systems.

Research into novel uses of optical fibres is examining the possibility of building a low cost perimeter protection system which not only senses when someone is breaking in, but also gives the position along the boundary. Similar systems will be able to be constructed for fire detection.

Optical fibres, engineered to have a very high sensitivity to vibration can be made to be thin enough to be concealed behind wallpaper and therefore virtually undetectable. This facilitates the construction of a covert listening device capable of monitoring disturbances in large rooms. Such devices are sensitive enough to pick up conversations from individuals a few metres away and the next generation will be able to detect the location of the source as well!

In 1986 the total worldwide security sensors market was split as follows :

	Value £ Millions
Acoustic	214
CCTV	452
Mechanical and Vibration	19
Microwave	101
Photoelectric & passive infra-red	191
Pressure	19
Proximity	28
Total world market for security sensors	£1024 million

From this it can be seen that optical technologies account for nearly 60% of the market with a value of £643m.

3.10.2 Imaging

Perhaps the largest potential for growth in the security industry comes in the use of imaging equipment. With the reduction in cost of CCD cameras, they can start to be used more liberally in security systems. Currently, such devices are used simply to relay images to a manual operator somewhere on the site being protected. However, with the increasing popularity of slow-scan, the operator no longer has to be on the site: instead he can be located in the alarm company's monitoring centre. The use of CCD cameras is already widespread and will account for 35% of all cameras used in security within 2 years.

There are many different CCTV systems on the market and the difference between their capabilities is largely dependent upon the camera tube technology employed. Each has particular strengths in terms of low-light capability, resolution, contrast ratio, weight, cost, etc and represent significant opportunities for new and improved products.

The next logical step in this development is to make the alarm control unit interpret the images to determine the presence of a fire or intruder, and then to relay the pictures to a central monitoring station or possibly the owner via a mobile cellular telephone as required. Previous systems have suffered from non-availability of adequate low cost powerful processors, were unsuccessful largely since they suffered an unacceptable level of false alarms. In the next few years, image processing functions aimed at pattern recognition, or movement detection, will be available in a single silicon chip. In five or ten years time, this processing may well be done in a monolithic optical computer, giving the sort of power required to make pattern recognition dependable.

3.10.3 Comments

Safety and security systems represent a niche market which the UK is well qualified and well placed to exploit. This was also recognised by the IT86 Committee which used the example of security and control of services and systems in domestic and commercial premises as the focus of one of their eight specimen projects. In any project in safety, security and control systems arising from consideration of the IT86 report, a key opportunity for the development and demonstration of novel techniques would be missed if optoelectronics were omitted.

3.11 Energy

As one might imagine, the domestic market for optoelectronic energy devices is small due to climatic conditions and the wide geographic coverage of grid-based electricity supply. The market is almost exclusively in photovoltaics and in spite of our inherent handicap, the UK is able to participate internationally with R&D and production being undertaken by BP Solar International and Intersolar together with research at Dundee University.

The size of the world terrestrial photovoltaics market is presently £300M and has grown steadily since its beginnings in the late 1970s. If the peak generating power capability sold each year is used as a measure of market size, the total terrestrial photovoltaics market has exhibited an average per annum growth rate of 40% to date. Table 3.11 provides an international comparison of production levels.

TABLE 3.11

WORLDWIDE PHOTOVOLTAIC SHIPMENTS (MW)

	1980	1981	1982	1983	1984	1985	1986
USA	2.5	3.5	5.2	12.7	11.5	7.7	8.7
Japan	0.5	1.1	1.7	4.3	6.2	8.1	11.4
Europe	0.3	0.8	1.4	3.3	3.3	3.5	3.7
Other	0.0	0.0	0.1	0.5	0.6	1.2	1.2
TOTAL	3.3	5.4	8.4	20.8	21.6	20.5	25.0

(Source: Solar Energy Insider's Report - September 1986)

3.11.1 Uses

Despite being a new market, clear differentiation has occurred. The major sectors are consumer, professional, space, recreational and village electrification. Grid connected systems do not yet constitute a true market since they rely on government funding of one-off demonstration projects or exploratory studies by utility companies.

Consumer applications include watches, calculators, battery chargers, clocks, and automotive roof panels.

Professional applications include, powering remote telecommunication repeater stations, cathodic protection, navigational aids, water desalination, and water pumping.

Recreational use of photovoltaically generated power is limited due to its expense at present. Deployment is occurring in yachting, caravanning and off-grid holiday homes.

Village electrification, a geographically diffuse market, uses photovoltaic power for lighting, television, radio and refrigeration.

3.11.2 Costs

The cost of photovoltaically generated electricity will fall as a result of the deployment of thin film photovoltaic technologies currently under development. An analysis of existing European remote power markets using diesel generated electricity and potential remote site new users forecasts a market of up to \$200M (equivalent to 50 MWp) per year if total system costs in the region of \$4/Wp can be attained. It should be emphasised that these figures refer only to Europe which is well served with grid electricity. Consequently, the worldwide market will be many times larger. Market forecasts for the year 2000 are of order \$5 billion.

3.11.3 Space applications

Space photovoltaics are growing slowly, entry to the market requiring considerable qualification of the product. Total market size over the next decade is estimated to be in the range of 100-200 kW and valued in the region of \$30-60M. The limited market size and cost of entry has resulted in few participants.

3.12 Components

The majority of the added-value in any market comes from the manufacture and supply of complete finished systems, though one of the primary reasons for undertaking R&D in components is to faciliate the early development of these systems. Traditionally the UK has lacked competitiveness in the component sector of most markets (except perhaps the automotive area) to the detriment of end producers since there are major disadvantages in the absence of an indigenous component supply industry. However, the components themselves represent a market opportunity for those prepared to commit to the high volumes necessary to achieve the economies of scale.

Selected areas of interest are discussed below.

3.12.1 Fibreoptics

Estimates for the current size and predicted growth of the fibreoptics component market are shown in Table 3.12.A. Projections on the detail are very difficult since 1985 and 1986 saw a huge increase in the installation of trunk capacity, which will not be repeated in later years. This has resulted in a temporary overcapacity in optical fibre, and possibly also a lull in the market for devices. However, after 1990 it is predicted that there will be strong growth in subscriber circuits and LANs, where the terminal costs outweigh the cable and optical fibre costs.

TABLE 3.12.A
Market for major fibreoptic components
(including fibre and cables) $M

	1985	1991
UK	92	332
France	65	330
W Germany	60	443
Europe	304	1460
USA	814	2000
World	1400	4200

(Source: European Markets for fibreoptics, September 1986)

A feature of the market in the 1990s will be a change from the sale of discrete devices towards the sale of transmitter and receiver modules. Another probable future trend will be a change from simple point-to-point links towards optical networks, which may cause the market for switches, couplers, multiplexers etc, to equal that for sources and detectors.

It should be noted therefore that simple projections based on currently available market data, largely produced over the past four years, is likely to be invalid in its detail due to the changes in the nature of the market. Table 3.12.B shows the main features of the 1987 market as currently seen.

Table 3.12.B

ESTIMATED WORLD MARKET FOR FIBREOPTIC COMPONENTS IN 1987

US Sales	50%
Japan Sales	25%
Rest of world	25%
Fibre and Cable	75%
Transmitters and Receivers	20%
Connectors	5%
Telecommunications	60%
Other Applications	40%
LEDs) by	25%
Lasers) value	75%
Sources	60%
Detectors	40%

(Industry estimates)

3.12.2 LEDs

The total world market in 1986 for LED numerical display was in the region of £200M, and that for LED indicators approximately £70M and fairly flat. Major growth may be stimulated by development of large panel arrays of LEDs for solid state illumination applications, eg vehicle lighting systems.

3.12.3 Lasers

The world market for lasers as components or sub-assemblies in 1986 was approximately $500M. Of this, the main 'commodity' market is in lasers for optical disc storage systems. The total world market in 1986 for this application was approximately £20M, representing a large volume (3 million devices) at a relatively low price. This will remain a large volume, low cost market with the growth of optical disc storage systems.

3.12.4 Processing components

Within the market for optical information processing devices, the spatial light modulator is a key component in the construction of competitive systems. The market is currently only around $10M per annum, but likely to grow as applications in projection displays mature to add to the optical information processing market.

3.12.5 Comments

There are many markets associated with the optoelectronics industry which the UK could exploit, eg connectors for fibreoptic cables.

It is often for their strategic value that companies have R&D programmes in components. Even if the mass market is not addressed, there is significant value in having early and proprietary access to research samples for systems R&D.

3.13 Materials

The market for materials and processing equipment is important not simply for its inherent business potential, but as infrastructure in support of all optoelectronics components and systems.

The total market for electronic materials is currently $8,000 million in the free world with Western Europe accounting for $1,000 million. Market research studies suggest a real growth rate of 12-14% per annum to 1990 and beyond. Of this, some 5-10% is likely to be optoelectronic materials, generating a world market of $400-$800 million, Europe accounting for $50-$100 million.

Specific market-oriented opportunities include:

- High purity materials and reagents.
- Fabricated layers and thin films of materials.
- Semiconductors.
- Chemical products with special physical and chemical properties for use in a wide variety of applications such as sensors, photo-resists, optical fibres, optoelectronic displays and reprographics.

3.13.1 Semiconductors

Although silicon will remain the workhorse of the microelectronics industry, semiconductors from the chemical groups III-V, such as gallium arsenide and indium phosphide which have distinctive electro-optical properties, will become more important for electronics in general and optoelectronics in particular. These III-V compounds are predicted to take 5% of the semiconductor market by 1990 and the challenge for the materials supplier is to produce high purity defect-free single crystals.

Thin film semiconducting structures will become increasingly important and present a considerable challenge in terms of chemistry and process technology. There will be a requirement longer term for electro-optic materials and non-linear crystals, and organic materials - a recent innovation - may become a market opportunity.

3.13.2 Special products

From the vast range of speciality products, areas of particular interest are:

i. Transmission, storage and display of data using optical means or a combination of optical and electronic methods is driving R&D for inorganic and organic chemicals and materials with special optical properties in addition to the III-V semiconductors mentioned above. There are also applications for polymers as optical cladding, protective sheathing and strength members, and possibly as the fibre core in competition with glass for low cost, short run fibres.

ii. Liquid crystal and electroluminescent displays require coloured pigments and new polymers are necessary to support and encapsulate the complete assembly.

iii. Photoconducting materials, used in photocopying equipment, are moving from selenium to organic materials with significant new opportunities arising for the application of colour chemistry and the use of polymer films.

3.13.3 Processes and equipment

Many processing techniques are geared to the delicate modification of surfaces or the intricate fabrication of ultra thin films and these rely on extremely pure materials. The semiconductor market imposes the most stringent specifications for purity (down to a level of impurity of only 1 part per million million), but ultimately chemicals for other applications are likely to have to match this standard. General purification technology needs to be developed further and there will be a continued need for high-purity reagents. Trends are from wet to dry processes and from liquid phase to vapour phase techniques. Amongst the techniques are :

- Chemical vapour deposition (CVD) - chemicals in the form of metal-organic or semiconductor-organic complexes are required.
- Plasma etching and deposition.
- Ion implantation using chemical dopant.
- Sputtering.

There is also a major market associated with the materials themselves in which the UK is relatively successful, and that is in the supply of manufacturing equipment. For example, Cambridge Instruments have notched up significant exports of their MOCVD equipment and III-V material crystal-pulling machinery.

4. TECHNOLOGIES

Technologies relevant to only one market have been described in the appropriate preceeding section. The following sections describe some of the key technologies which are applicable to a range of markets.

The degree of concentration of expertise; funding and investment, both private and public; the influence of major customers, both private and public; standards; and manpower and training are examined as appropriate dealing in turn with: basic research, applied research, development and exploitation.

Potential applications of the technology, dealt with in the previous market sections are mentioned in some cases, but it has not been practicable to segregate the technologies from their applications in all cases, neither would it have been sensible to do so.

Most subsections conclude with some general comments on the technology which are taken later with the comments from the market subsections and the common threads drawn together in section 7 COMMENT.

The sections are technical in content, but a detailed comprehension of this chapter is not essential to an understanding of the remainder of the report. A list of abbreviations and a glossary are annexed to the report.

4.1 Materials

In the development of any new technology, the underlying science is the bedrock upon which the edifice is constructed. For optoelectronics the availability of relevant materials is paramount. The UK has been involved significantly in the evolution of many of the new materials used in optoelectronics, for example, in the early investigations of compound semiconductors through RSRE, associated MoD establishments and industry.

A Japanese report illustrates the growth of optoelectronic technology in the form of a tree (Figure 8). Materials form the roots of the technology tree, whose health (success) in terms of blooms (successful market applications) is determined by the soundness of these roots. This evokes the key nature of materials, processing techniques and characterisation.

Inorganic optoelectronic materials work can be divided thus:

1. Starting materials - Chemicals of ultra high purity, often exotic and scarce.

2. Bulk materials - Including glass, crystal growing and ceramic manufacture.

3. Epitaxial techniques - Involving a variety of techniques, originally pioneered by the semiconductor industry.

Organic materials are considered separately.

4.1.1 Starting Materials

The purity of starting materials is vital for successful optoelectronic device manufacture just as it has been for the semiconductor industry. The UK is well served by companies specialising in the supply of such materials (Johnson Matthey and BDH for example), who offer their products to a range of industries.

The development and manufacture of the material must be supported by analysis facilities which currently are available as services from universities and Government laboratories (eg UKAEA at Harwell) and within industrial companies.

The UK is well placed for starting materials and characterisation through a good investment record by companies, research laboratories and universities. This investment has continued in the JOERS scheme, particularly in organic materials, the precursors of III-V compounds, and in zinc sulphide chemistry.

A list of applications for high purity chemicals in optoelectronics would include crystal growing, coatings, developers, fluorescence, luminescence, photo-sensitive phosphors, dyes, etc.

4.1.2 Bulk Materials

The transition from starting material to bulk material can be examined by considering the process involved. In fact almost independent technologies and corresponding specialist technologists have evolved.

4.1.2.1 Glass

This is a well established mature technology with a wide range of products. Centres of excellence exist in universities (Sheffield and Southampton) and within Companies (eg Pilkingtons), which are able to develop new types of glasses. There is a danger that the age and maturity of the technology may result in conservatism unless there is a clear market application or major customer lead. An example has been low-loss glass for optical fibres where the strong market focus has stimulated industry to satisfy demands.

Material engineering in glass depends on the addition of active dopants, (photochromics, lasers), surface treatments (optical discs, waveguides), alteration of form (fibres) or a combination of these (fibre sensors). There is on-going UK work in fibres at STC, BT, GEC, and York Technology. JOERS has funded work on longer wavelength optical fibres. There has been significant MoD funding on bulk infra-red transmitting glasses mainly with Barr and Stroud. In general, industry appears able to satisfy market needs.

4.1.2.2 Crystal Growing

A wide range of crystals are available world-wide, a number of which are produced in the UK. The applications cover the following functions:

Acousto-optic	Electro-optic
Birefringent	Magneto-optic
Solid-state laser	Windows
Semiconductor	

In the USA, defence contracts are often the driving force for materials research, but there is not the same breadth of coverage in the UK. Under JOERS, there has been a substantial programme to develop lithium niobate for integrated optic applications. ICI supply wafers of GaAs and InP from a new factory and MCP supply a wide range of III-V compounds and other semiconductors. Outside JOERS, there is little research focused on new crystals or crystal growing techniques. The main government research centre is RSRE, the programme being funded jointly by DTI and MoD. Cadmium mercury telluride for infra-red detectors is grown at RSRE and by Phillips (Southampton).

4.1.2.3 Ceramics

Ceramic materials have not been widely used in optoelectronics, although ceramics based on lead zirconate titanate are used in pyroelectric detectors and in optical modulators. The necessary expertise exists for their manufacture, although only the pyroelectric materials are currently made. There is a much wider activity in the USA and Japan.

4.1.3 <u>Epitaxy</u>

Many devices require the growth of thin epitaxial layers on a substrate of the bulk material. The semiconductor industry pioneered the development of a variety of liquid, vapour and vacuum growth techniques which are exploited in optoelectronics. In epitaxy, there is close association with the ultimate component: as a consequence, it holds many attractions as a flexible materials engineering technology for the design of a widely applicable range of devices.

BT, GEC, Plessey and STC have made major investments in epitaxial growth R&D by all three methods for growth on GaAs and InP. The early methods of growth from liquid melts and by vapour phase growth from the chlorides have been supplemented by growth from metal organic compounds (MOCVD) and by molecular beam epitaxy (MBE). These methods allow complex multilayer structures to be made with layer thicknesses as low as one or two atomic diameters. Some of the early work in epitaxy was done at government laboratories by the Ministry of Defence which is still undertaking some research, both internally and by external contract.

Sheffield University forms one of SERC's microelectronics facilities, supplying epitaxial samples to university users and undertaking research. Research involving epitaxial growth of compound semiconductors is also undertaken at Glasgow, UMIST, Nottingham, Cardiff, Oxford, Cambridge and Imperial College. Most of these universities are funded under the Low Dimensional Structures (LDS) Initiative whose objectives are only partly relevant to optoelectronics. Industrial and university research in epitaxy (at UMIST, QMC, Oxford and Sheffield) forms a part of the JOERS scheme. The DTI and SERC have recently launched a LINK programme of collaborative research in advanced semiconductor materials. This will mainly focus on material studies related to multilayer superlattice structures and on novel electronic and optoelectronic devices using such structures.

The Japanese are making very large investments in these technologies, particularly MBE. There is much in common with their aspirations for the 5th generation computer concept arising out of electronic investment in VLSI.

4.1.4 Organic Materials

Developers of optoelectronic devices search for 'ideal' materials so that their products can be smaller, cheaper and more efficient than their competitors. The intrinsic non-linear properties of some organic materials are superior to the established inorganics, but the challenge is to produce the materials in a form and of sufficient optical quality for the device requirements. The processing of the materials again splits into bulk and epitaxial techniques.

The engineering of organic materials has been intensively developed over many years, notably in the chemical and drug industries, but it is only relatively recently that this knowledge has begun to cross the boundary into optical signal processing. Prominent examples are the development of lasing dyes, Langmuir-Blodgett films and liquid crystals. The major chemical companies are now seeking smaller volume, higher value added materials applications. In optoelectronics they confront major problems in modelling and engineering high optical quality materials to achieve predicted optoelectronic properties and in devising suitable device configurations.

Single crystals of organic materials have been produced over a number of years largely by solution growth. There are several centres of expertise in the UK: eg, ICI, BP and Stratclyde University. JOERS is supporting substantial amounts of work on bulk organic materials and liquid crystals. The liquid crystal work takes up research originally undertaken by the Ministry of Defence at RSRE and Hull University, and is exploited by BDH at the level of materials sales.

There is little background in epitaxial growth of organic materials, unlike optoelectronic semiconductors where processing of similar materials for electronic components is well established. There is therefore considerable scope for innovation. JOERS has supported work on polymer fibres and liquid crystals, and it is expected that funding will be forthcoming under both the RACE programme (for research into polymer based integrated optics) and the new LINK Programme in molecular electronics (which includes research into organic materials with optoelectronic properties).

4.1.5 Comments

The great diversity of materials used in optoelectronics suggests that the UK will rely in part on external sources. In fact, the UK position is quite good in many areas as a result of past funding by Ministry of Defence and BT, present investment by industry and DTI and university research within JOERS. The increasing degree of integration of many functions within a single technology implies that the important materials technologies must continue to be available locally by any country aspiring to a major role in optoelectronics. The epitaxial technologies for III-V compounds must be the subject of continued R&D, focused towards optoelectronic activities. More broadly, materials research towards future optoelectronics must be supported to ensure that foundations similar to those we are building on today are available to the next generation of technology.

JAPANESE TREE OF OPTOELECTRONIC TECHNOLOGY

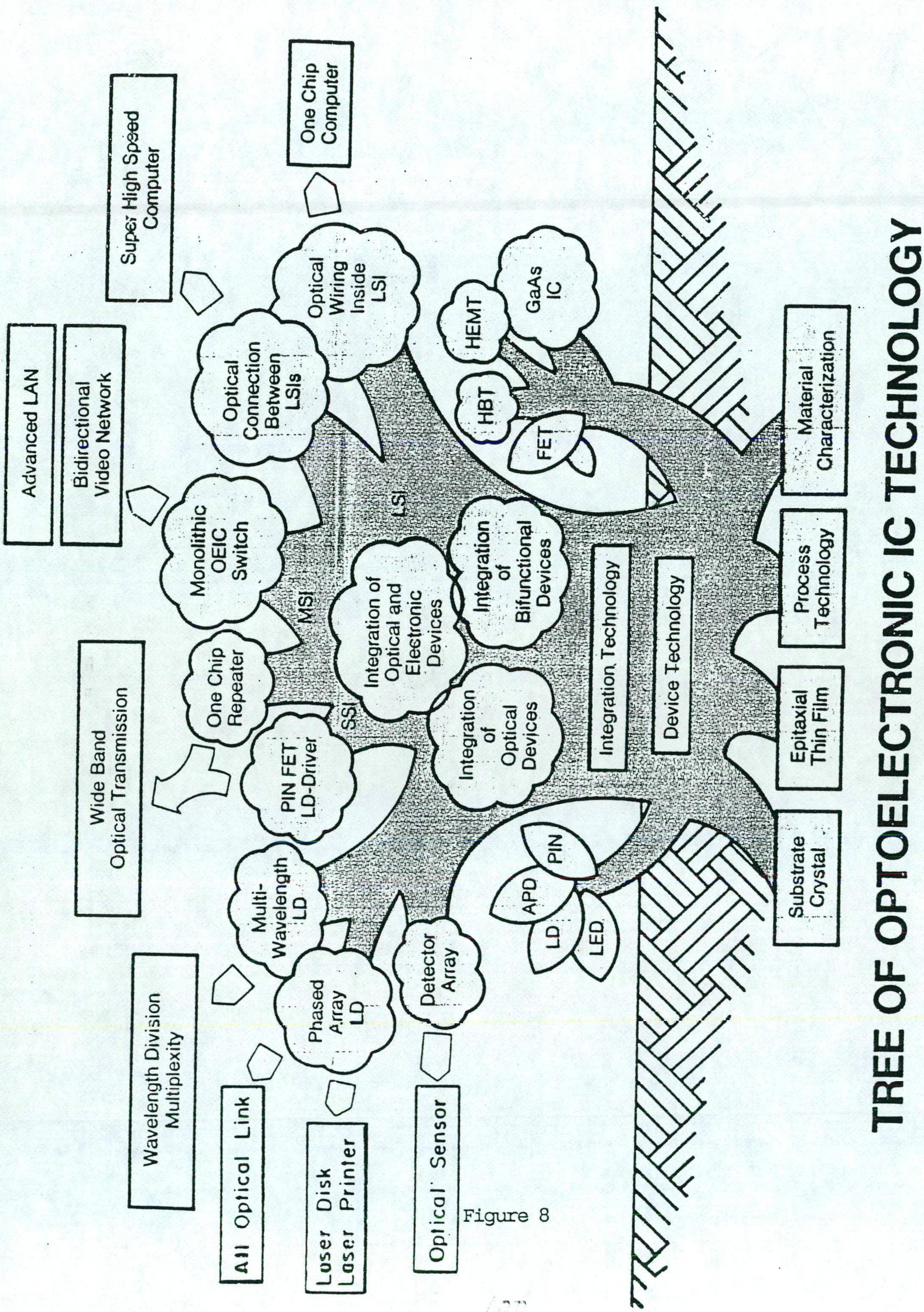

Figure 8

4.2 Transmission and switching systems

4.2.1 Transmission systems

The impact of optical fibres on long-distance, point-to-point, telecommunication has been dramatic. Compared with coaxial cable, transmission distances between repeaters have been increased by well over an order of magnitude to almost 200Km; the bandwidth of a fibre is for most practical purposes almost infinite; the small size of optical fibre cables greatly facilitates handling, installation and laying; whilst the freedom from electromagnetic interference and sparking hazards allow them to be installed in situations which would otherwise be prohibited.

The early installations by BT were low bandwidths 2, 8 and 34Mbit/s systems in multimode fibre. Such a choice eases the problem of fibre connection, but limits the length and bandwidth of the fibre, as rays taking different paths in the fibre cause distortion of the pulse shapes and ultimately, loss of information. All their future systems will use 8/125 single mode fibre (ie an 8 micron diameter core carrying the signal and a 125 micron outer region). In the trunk network BT use 140Mbit/s as standard, 565Mbit/s when required and 240Mbit/s in experimental installations. Mercury also use 140 and 565Mbit/s trunks. The Japanese use 400Mbit/s trunks and have demonstrated links up to about 10,000Mbit/s.

But most attention is now focused on the local network that the trunk network serves. A single digital telephone channel uses 64Kbit/s. Businesses typically require up to 2Mbit/s of bandwidth but the demand for high speed data (or high volume file transfer) will lead to demands for 100Mbit/s into the local exchange as mentioned in Section 3.1. Some of this data will be circulated in local area networks (LAN) with different protocols from the public networks creating a demand for interfaces between the public networks and the (private) LANs. Conference videophone may be provided from 2Mbit/s upwards though normal TV requires 140Mbit/s. The RACE programme assumes that businesses and domestic consumer will require 4 simultaneous TV channels, selectable from many by the consumer. Such bandwidths of course are much less than required for widespread use of videophone, say 2Mbit/s each which will generate a volume of traffic ultimately comparable with telephony but needing thirty times the bandwidth. At this stage, or before, it will no longer be appropriate to send all traffic on a single broad optical carrier, but to divide traffic from different sources by wavelength.

Ultimately, the wavelength of the optical carrier can be defined very accurately allowing each source its own frequency, as in radio. Under these circumstances the techniques of coherent detection used in radio will allow highly selective low noise detection of individual subscribers and increase the bandwidth of each fibre almost indefinitely.

Despite these massive advances the technology is still, in telecommunication terms, in a comparatively primitive state. This largely comes about because the sources available, namely laser diodes, are effectively optical noise generators, lacking adequate coherence, so that installed systems are normally limited to some form of amplitude modulation and incoherent detection. In addition, there are very few circuit components available, such as couplers, isolators, filters, resonators, circulators, and so on, that are taken so much for granted at microwave and lower frequencies. In order to exploit optical fibre communications to its full extent the first requirement is the development of at least quasi-monochromatic laser diodes, that are also robust, reliable, efficient and not too expensive. The second requirement, of equal importance, is the realisation of passive fibre components to provide the necessary circuit processing functions. These circuit elements are vitally necessary also for the successful extension of fibre transmission into local-area networks.

The ability to transmit information on a single optical fibre now greatly exceeds the capacity of the associated sources, detectors and electronic components to process it. There is therefore a need for more complex optical signal handling. A considerable amount of work and funding has been and is still being expended on integrated optical devices but few practical devices have yet emerged.

4.2.2 Switching systems

Indeed the architecture of future telecommunications systems no longer makes the clean separation between the exchange and the passive transmission network that is possible today. The switching modules must allow a number of wideband inputs to be routed to arbitrary output positions. The control of the routing may result from external control signals or may be derived from the signal packets themselves. Although in the short term silicon technology will be used in conjunction with conventional optical transceivers, in the longer term integrated optics may prove more powerful. Arrays of electro-optically switched directional couplers may be configured as switching matrices using lithium niobate or III-V technology. The latter may be more powerful for packet switching. More radical solutions are possible using digital optics.

Optical signals can also be routed by means of wavelength, using a fibreoptic network as a guided-wave medium in the way that radio or microwave uses free space. Using direct detection technology, a number of discrete wavelengths and hence parallel channels can be supported: using coherent detection, this would increase to theoretically thousands of channels.

4.2.3 Comments

Priorities urgently need to be established between the various possible network topologies followed by a programme of demonstrator projects involving major subsystems. According to the technology proposed, these might be established almost immediately if based upon a directional-coupler or wavelength circuit-switched technology: or in a few years if based upon a packet-switched approach, whether using digital optics or directional couplers.

The programme will be closely related to RACE and may be in competition. It would be desirable for the UK participants to agree on a common strategy outside the RACE programme so as to present a common front to Europe and to counter some of the major positions now being taken by the USA and European groupings.

4.3 **Components for communications systems**

For the present and near future, most communication systems are simply point-to-point optical links with all the multiplexing and switching performed using conventional electronics. In these systems the key optoelectronic components are:

Optical fibre and the cable into which it is incorporated
Transmitters and receivers.
Connectors.

In future systems, particularly complex networks, new architectures will be used and these will depend on the availability of new components. The list cannot be complete until the issues of system architecture have been resolved, but it can be foreseen that there will be a need for at least:

Components for coherent systems
- Narrow linewidth lasers, frequency controlled local oscillators, couplers, phase modulators, amplitude modulators, polarisation controllers etc.

Components for wavelength multiplexed systems
- Multiplexers and de-multiplexers, (variable) frequency selective couplers and switches.

Components for new network topologies
- Star couplers, flexible access taps, optically activated switches, optical amplifiers etc.

There are a number of different technologies which may be relevant to these new component concepts. Optoelectronic devices constructed from III-V materials will play a significant role since both optical and electronic functions together with passive devices can be integrated on the same chip. These devices, known as optoelectronic integrated circuits or OEICS are capable of performing extremely complex functions. Other technologies which will also have a place are fibre-based components and integrated optics. However, since this is currently a rapidly moving and somewhat speculative field and the useful components will evolve from a close interaction between the component technologists and system researchers, the key to the UK strength is to have a balanced portfolio of basic technologies available, with the objective of enabling the excellent progress in the '70s and '80s to be maintained into the '90s for the second and third generation systems.

4.3.1 Optical fibre and cables

4.3.1.1 Optical fibre

Almost all present communication systems use optical fibres made from very high purity silica which is doped carefully with specific elements to create a "core" in which the light travels and a "cladding" to prevent external influences on the core. Standard sizes are multimode with a 50 micron core in a 125 micron fibre and single mode with an 8 micron core in a 125 micron fibre. The fibre is always coated with a layer of polymer to protect it. Alternatives, such as multicomponent glass fibres have been developed but are inferior to silica types. There is a possibility that new materials, such as fluorides, may give lower attenuation at longer wavelengths and a few companies around the world are carrying out research. However, in view of the very highly developed technology for silica and the extreme difficulty of purifying and handling the new materials, it is most unlikely that they will make any significant impact on the fibre market during this century.

Silica fibre technology is very highly developed and can be considered now to be a maturing business. A number of different processes are used but all the successful ones are based on the deposition of silica from chemical vapour sources. A large (in the region of 1m x 20mm) cylindrical preform is produced and this is drawn into long lengths of fibre. The Corning process uses deposition on the outside of a mandrel, the Sumitomo process uses axial deposition to produce larger preforms, and the process used by ATT and many others (including STC and GEC in the UK) is to deposit the silica on the inside of a silica tube. All have their advantages and disadvantages and all are in large scale production. The main development emphasis for standard fibre types is to achieve lower costs by making larger preforms at higher yield. The UK is well situated with three manufacturers producing competitive fibre, despite having an installed capacity much smaller than, for example, the USA.

Research and development in this topic is largely concerned with new fibre designs to enhance the optical performance. Although attenuation is routinely close to the theoretical minimum, for very long communication links the performance is affected by dispersion (the result of different wavelengths of light travelling at different speeds through the fibre). Two methods of tackling this are being investigated, either using standard fibre with a very narrow linewidth laser source, or modifying the fibre to minimise dispersion at the operating wavelength. Progress in lasers is making it more probable that the issue will be resolved at the transmitter end rather than changing the fibre, but this remains an open question at present.

Other active research topics concern special fibres for military systems where a more difficult environment is encountered, and special fibres for sensor applications rather than for communications. In addition, the latest work concerns the use of specially doped fibres which can be used as lasers or amplifiers and special fibres tailored for use in passive fibre-based components. In all these areas the UK has a good position, partly because of the excellent work carried out at Southampton University, and partly as a result of MoD funding in industry over the past 15 years. The route to exploitation of special fibres is, in principal, clear with industry equipped to make all but the most recent inventions. However, the markets for special fibres have been slow to develop so for the moment, suppliers are concentrating on standard products.

With the emphasis in the communications field moving towards shorter, more complex networks, as opposed to larger and higher capacity networks, the performance of fibre no longer appears to be a significant strategic issue. The intellectual content of the majority of future systems lies in the terminals or nodes. Thus the level of research into basic fibre design and technology can be expected to be lower than in earlier years.

4.3.1.2 Cable

Since the cable aspects are not specifically "optoelectronic", this topic is not covered in great detail. However, it should be remembered that the optical cable business currently represents a large proportion of the total optical communications business (estimated to be 25% in 1990).

A very significant amount of research and development has been done and continues on optical cable structures. Since fibre is sensitive to stresses of several kinds, (stretch, transverse compression, bend, regular microbends etc.), the job of the cable package is to ensure that the required optical and strength performance is achieved under all the desired environmental conditions. Many designs have been developed and these fall broadly into 'loose' construction with the polymer coated silica fibre lying loosely in an oversize tube or channel, or 'tight' construction, in which the fibre is closely surrounded by compliant material and is firmly incorporated into the cable structure. At present the former is almost universally used for telecommunications applications, being cheaper and requiring less of the fibre specification, whereas the latter is more suited to rugged environments so is often used for military cables etc.

The position of the UK is good with competitive technology for telecommunications cables, and world class technology for special military and industrial cables. A particular strength is in undersea telecommunication cables in which STC has a large part of the world market.

4.3.2 Transmitters and receivers

Until recently the tendency has been for specialist suppliers to sell discrete components which have been built by the equipment manufacturers into the optoelectronic equipment. In future the trend will be rapidly towards the sale of modules with a purely electronic interface and with more and more of the "transmitter" and "receiver" being integrated into the module. Thus more of the added-value will lie with the equipment manufacture. For this reason alone it is vital to have UK sources of the key components. However, other reasons include the strategic nature of such specialised components, in that many of the competing equipment manufacturers are vertically integrated and can control the availability of state-of-the-art components.

4.3.2.1 Device Types

These comprise laser diodes, light emitting diodes (LEDs) and detectors operating at three principle wavelengths:

0.85 micron - used for short distances
1.3 micron - currently used for long distance systems
1.55 micron - will be used for highest performance/longest distances.

The devices are used for two types of fibre: single mode and multimode.

4.3.2.2 Basic materials

All laser and LED sources are made from III-V semiconductors. Detectors for 1.3 and 1.55 micron either use germanium, or more commonly, III-V semiconductors.

Since almost all III-V devices use heterojunctions, a key to their fabrication is the growth of multiple thin layers of different compositions. For 0.85 micron devices the materials are in the GaAs/Ga(x)Al(1-x)As system and for 1.3 and 1.55 micron the materials are in the InP/Ga(x)In(1-x)As(y)P(1-y) system.

Four growth techniques are suitable for producing these layers: Liquid Phase Epitaxy (LPE), Vapour Phase Epitaxy (VPE), Metal Organic Chemical Vapour Deposition (MOCVD) and Molecular Beam Epitaxy (MBE). LPE has been used successfully for many years for laser diode and LED sources and VPE has been used for detectors. MOCVD and MBE both have advantages in control of composition and geometry and currently MOCVD looks as though it will be the optimum technique for large area epitaxy suitable for volume production at low cost. MBE remains largely a research tool.

4.3.2.3 Device structures

The performance of devices is critically dependent on both the quality of the material and on the ability to accurately control fine geometries. Very many device structures exist with various advantages and disadvantages. For example, one structure may be chosen to give high reliability whilst another may be chosen to give low operating current, or a third very low cost in high volumes, all with compromises in other parameters. Thus the industry is full of proprietary designs which tend to fulfil particular market needs, rather than standard products from several manufacturers. This situation may mature in time, but it complicates the analysis of competitive positions.

4.3.2.4 Key players

The main UK industrial expertise is currently in STC and Plessey. There is R&D effort in GEC but product is not yet available. An important new activity is the joint company BT&D which will use BT technology and Du Pont manufacturing expertise and plans to be in production by mid 1987.

Funded by MoD DCVD Directorate in the `60s, together with British Telecom in the `70s and then also DTI, seedcorn investment concentrated laser R&D at STC with Plessey concentrating on LEDs and detectors. Although each now sells all three components, the market positioning reflects this initial investment.

In the USA the main strength is in start-up companies, some of which have grown quite large. There are a large number and mostly they specialize in particular product niches. In Japan, as in Europe as a whole, the main strength is within the major electronics companies who are largely vertically integrated.

No major university groups specialise in materials and devices for sources and detectors, although some are involved in particular aspects and related technology. Those with a major interest are:

Sheffield	LPE, MOCVD, MBE, some devices
Glasgow	MBE, integrated optics
UMIST	MBE, MOCVD, assessment

Others are involved in materials assessment, novel device research etc, but without a self-sufficient technology base.

4.3.2.5 Research and development

Progress in this area benefited enormously in the early days from MoD (DCVD) research and development funds. At the later stages there was also significant BTRL funding and, importantly, technical collaboration which accelerated the industry programmes. In recent years there has been very substantial DTI investment in both research and product development.

Each of the major laboratories now has a team of around 30 people developing new technologies for materials growth and device fabrication with considerable emphasis on future needs, such as single frequency and coherent lasers, high speed higher output LEDs, integration of optical and electronic functions etc. All the programmes are heavily company funded with a small MoD content together with significant grants from DTI and EC on collaborative programmes. In addition to the research scientists employed in the central research facilities; STC, Plessey and BT&D have experienced optoelectronic development and production engineers in their manufacturing companies.

The basic technology for sources and detectors has benefited considerably from the JOERS scheme, although devices themselves have not been covered. The development of the MOCVD process for 1.3 and 1.55 micron geometries is an excellent example of effective collaboration. ESPRIT and RACE programmes are also of benefit although the mechanisms of international collaboration are more cumbersome.

A key to the future is investment in production engineering to achieve high volume, low cost components. Both STC and BT&D have significant investment programmes for this activity. Both are behind the Japanese, in that NEC (at least) have built a purpose-designed factory for low cost production of devices through to modules.

4.3.2.6 Competitive position

Most of the activity in company funded R&D over the past 10 years has been as a result of the need for early supply of in-house components, with a secondary aim of addressing the world market. Although this has now changed somewhat, with considerable investment towards world markets, the result is that the present strengths of the companies are a reflection on their own system needs. Thus STC, with its strength in undersea systems can currently supply the worlds most reliable 1.3 micron lasers, whereas Plessey, with early concentration on multimode systems, developed a strength in LEDs and high sensitivity receivers. Arriving late in the market place, BT&D will aim directly for the volume markets. Thus UK companies have a good competitive position in their chosen niches though not currently in any high volume mass market applications which would benefit future communications markets.

4.3.2.7 *Future developments*

Fibreoptics has so far only scratched the surface of its potential applications. With its obvious advantages for long haul transmission fibre optics has totally dominated this field and will become more a major competitor with satellite transmission even for very long haul transmission. Landline trunk transmission is becoming saturated with overcapacity already in the USA. However, optics will penetrate further and further into IT products to subscriber connections, office wiring, board interconnections, chip interconnections and into all optical processes.

As applications grow in local area systems, the "terminal" becomes relatively more and more important until optoelectronic sources and detectors ultimately form a much larger part of the total market, whilst the optical fibres themslves decrease in importance.

There is currently much uncertainty over the way in which optical systems will develop. With the advances in coherent optics there will be the possibility of multichannel broadcasting over a fibreoptic network. The transmitters and receivers would have to be much more complex, though still subject to stringent cost constraints, and there would be a need for an exended range of passive components, eg couplers, modulators, and OEICs (see later section).

4.3.3 Connectors

Although splicing may become more widely used to join monomode optical fibre in the construction of large scale networks, demountable connectors are a vital part of any optical communication system. At times in the past, the absence of suitable connectors has caused significant difficulties. The need is for very great mechanical precision and low cost combined with environmental ruggedness. The situation is now reasonably good with the traditional connector manufacturers (eg Canon) becoming involved. In future there will be a need for very low loss connectors for more complex systems where many connectors may occur in a single path.

4.3.4 Optical fibre based components

As described in section 4.2, there is a need for a whole new range of components for the next generation of communications systems. Many of these can be constructed from elements of either standard or specially doped fibre or fibre with special geometries. For example, simple couplers can be made by twisting and carefully fusing short lengths of fibre together. The advantage of this type of component is that it is easy to make, has low loss and interfaces ideally with the transmission fibre.

4.3.4.1 Passive Components

Probably the most important device is the four-port or multi-port coupler. Well developed devices are already on the market and the main requirement is for cost reduction in the future. Polarisation selective couplers and wavelength selective couplers are needed for some applications which currently exist in laboratories in the UK, but are not yet commercially available. A range of other devices such as isolators, filters, variable couplers are also needed, but are at an earlier stage.

A key component in future will be a method of accessing fibre, equivalent to the demountable cable clip which can be used with conventional metallic cable.

4.3.4.2 Active Components.

A new field of research into active fibre components has recently developed. The high quality and unique configurations that have been shown to be possible in fibres provides very high performance, especially when non-linear effects are exploited. For example, the shortest pulses and the fastest gates have been made in optical fibres, which are also particularly suitable in applications requiring long delays, uniformity and power-handling capability. Silica is a good material for very fast non-linear optical processing and is capable of providing an optical, or an electro-optical, facility operating on a number of channels and complements the parallel optical capability of the digital optics approaches. Optical fibre logic can handle very high data rates in fewer channels for communications, multiplexing and fast data acquisition, compared with the highly complex parallel processing of digital optics at lower speeds.

Possible active fibre devices range from new types of optical source, to in-line optical amplifiers, optical harmonic generation, wavelength shifting, optical mixing, modulators, switching, gating, pulse compression, optical bistability, memory and direct electro-optic interfacing.

4.3.4.3 The UK Position.

New fibre components are likely to have a major impact on the development of optical signal processing techniques in telecommunications, sensing, control and instrumentation generally. These components will be crucial to the manufacture of new sub-systems and systems, and thus to be a significant force in these products, it will be essential to have ready access to the technology of the new fibre components and not be at the mercy, and behind the technology, of foreign suppliers.

The UK is in a strong position at the present time, in part due to the success of the JOERS programme on advanced fibre waveguide devices. The proposed continuation of this programme covers optical generation and amplification based on the new lasing fibres, control and dividing functions, new and special fibres, switching, gating, compression, bistability and subsystems. Whether it will be possible to turn this R&D advantage into a commercial advantage remains to be seen.

4.3.5 <u>Optoelectronic integrated circuits</u>

There is a topic area is often called 'integrated optics'. It refers to the use of optical waveguides in a suitable material, almost universally lithium niobate, to carry out optical circuit functions. This is particularly good for some functions, such as phase modulators, routing switches, amplitude modulators and passive waveguides, splitters etc. There is a problem with interface losses to fibres but the field is now quite well developed and has benefited significantly from the JOERS scheme. A range of components now exists in laboratories (BTRL, Plessey, STC) and the exploitation phase is awaiting the development of the market for the systems which depend on these components.

There is a distinctly different field referred to as 'integrated optoelecronics', or Optoelectronic Integrated Circuits (OEICS). This covers the use of active materials, currently III-V semiconductors based on GaAs or InP to effect the integration of optical functions (lasers, LEDs, detectors) with electronic functions (transistors and diodes for switches, amplifiers etc) and with the additional capability for including passive waveguides for interconnection and active waveguides for modulators etc. Because of its much greater functionality, the use of III-V OEICS is likely to be by far the more important topic in future years. One speculative aspect is that if III-V materials can be grown on silicon, then there will be the opportunity for a comprehensive silicon/OEIC integrated technology with obvious further advantages.

In addition to their application in communications, OEICS are likely to be key components in optoelectronic information processing.

The benefit of integration is not just that of lower costs but also improved performance due to, for example, lower interconnection delays, smaller interconnection losses, higher density of laser or detector arrays, stability of optical performance etc.

The technologies needed for OEICS are largely a combination of those needed for sources and detectors plus some from the field of III-V integrated circuits. The UK is currently well placed in these basic technologies. Work is currently being expanded in a number of laboratories in addition to new projects under JOERS. There will most probably be programmes under ESPRIT and RACE also. What is lacking in the currently projected scenario is the presence of significant demonstrator projects, equivalent to those in Japan, which will pull through the technology and drive it towards real applications.

4.3.6 Comments

The development of new types of optical fibre systems, having a wide variety of applications, will be crucially dependent on the creation of suitable components. The UK is in a leading position at the present stage of the technology, which could be classed as an "enabling" technology for future subsystems and systems. It is therefore essential that the current research expertise is translated into commercial success.

In addition, the penetration of optics depends on the cost effectiveness of the technology. Thus the availability of low cost components is vital, and since a major part of the cost is frequently the sources and detectors, having a share in this business becomes vital for the UK. To be a successful manufacturer of these components companies must aim for a significant share of the available world market. In-house supply alone eventually leads to uneconomic production. UK companies have been successful so far, for example STC currently has 15% of the accessible world market for semiconductor lasers. However, competition is now much more fierce and to retain this position the UK needs investment in production engineering and a large home market. This has been the key to Japanese success both in this and other fields.

Whilst the JOERS programme does not support discrete device fabrication directly, its funding of materials research is crucial in underpinning the development of competitive sources and detectors. It is therefore important that this avenue of support for strategic research is maintained.

The lack of a substantial research effort in devices within universities has not been of direct impact itself, but it has meant that very little post-graduate training has been undertaken in device technology. Industry has had to train its own staff with a significant reduction in available resource, compared to Japan and the USA. This has hindered progress during the past 5-10 years.

Although integrated optics has taken rather long to mature, it is regarded as a very important development world-wide. It is important that the UK does not find that developments based on discrete components are overtaken by this new technology. Foci for these new optical IC technologies are required within large system demonstrators, or as small-scale demonstrators in their own right.

4.4 Optical information processing

The rapid growth of interest in the possible use of optical logic has highlighted two potential attractions, parallelism and speed; but equally significant are the opportunities that exist for entirely new approaches. Optics has been cited as a promising solution to a variety of current limitations in computing problems. Already optical fibres are being used for inter-system communication and a number of the new generation of digital electronic machines have 'optical back-planes' linking processor and memory boards within a single system. It is likely that optics will permeate through to all levels of computing systems, down to, and including the logic elements themselves. The natural parallelism and wide bandwidth available from simple optical systems can be exploited in a number of ways for providing space wiring between logic planes such that novel system architectures can be implemented. Optics also offers an attractive alternative for providing logic gates. Optical processing should therefore offer solutions to some of the major problems that confront computer system designers at present, such as clock skew and interconnection bandwidth.

Optical circuits are potentially capable of much faster operation than electronic ones, switching speeds extending into the sub-picosecond range, and although discrete electronic devices can operate at picosecond speeds, complex circuit interconnections are very difficult to design to exploit switching delays of less than a hundred picoseconds. This suggests a need for non-linear optical logic devices targeted either within the range of 0.1 to 100 ps switching delay, or up to microseconds if the advantages of large scale parallelism are utilised. Control functions could be either optical or electrical to optimise sensitivity and interfacing.

Specific topics where there is significant R&D are:

i. Acousto-optic methods make use of sound waves to induce a dynamic diffraction grating on the surface or in the volume of a material upon which the information-bearing optical beam impinges. The use of this Bragg reflection with a detector array leads to a practical frequency spectrum analyser.

ii. The use of nonlinear optical circuit elements, first demonstrated in the UK, opens up the possibility of logic decision making purely optically. Arrays of such optical logic gates and read/write/erasable memory devices could have direct optical communication with each other and operate in parallel. Digital all-optical circuits have been shown to make extensible restoring digital optical logic possible. The concepts and the possibility that optical switches and optical short-range communications can be faster than electronic circuits have promoted speculation about 'optical' computers, but these are likely to include some electronics for the foreseeable future.

iii. Use of lenses and spatial filters: a lens can readily achieve the mathematical process of Fourier transformation. Substantial processing using matched optical filters has been shown possible by computer modelling. To achieve this in real time - eg for target recognition a dynamically reconfigurable optical spatial filter is a requirement.

iv. Specialised application of optics such as the use of optical fibres as delay lines for the high frequency pulses of radar technology.

Few usable systems have yet emerged. One which has is that for synthetic aperture radar (SAR). Airborne radar target seeking can produce input very intensive in digital computer terms - a typical mission requiring a whole day of computation. An experimental optical processor in service in the USA has shown that this same task can be done in real time. This example illustrates why a substantial world wide research effort is now focusing on these general possibilities of optoelectronic data processing.

4.4.1 Hardware

The three characteristics of light which can be exploited are natural parallelism, non interfering propogation and high bandwidth.

One series of devices currently much researched are called, variously, spatial light modulators (SLM), liquid crystal light valves (LCLV), and optical transphasor array processors (TAP). These are the basic building blocks for optical information processing systems, with about 30 different varieties under development, a few of which are in commercial production.

The absence of viable spatial light modulators has been a major obstacle to the exloitation of 2-D optical signal processing for many years. The problem also affects image processing because the Fourier transform relationship (eg of a lens) requires an incoherent-to-coherent converter. Thus a considerable amount of research effort world-wide is being devoted to a solution of this problem.

About 25 industrial companies are active world-wide, mainly in the USA and Japan. The front-runner, Hughes Corporation, with its liquid crystal light valve reports annual production of roughly 300 units (valued at $25,000 each). The applications of these components extend beyond optical information processing into projection displays, which are covered in more detail in section 4.6.6.

In the UK GEC, STC, British Aerospace and Edinburgh Instruments have small programmes in this area out of which products are beginning to emerge.

4.4.2 Digital optics using non-linear elements

A new direction of research was begun in the late 1970's with the discovery of optical nonlinearity and optical bistability leading to optical transistors with gain, resettable memory devices and the separate success of read only optical memories setting a scene for new directions in computing, broadband switching and display technologies.

In research terms, there have existed several communities investigating

"Optical computing" - devoted to analogue optical computing;

"nonlinear optics and optical bistability"; and

"computer architecture" with an increasing emphasis on parallel processing.

Two arguments are put forward:

a. Electronics, at elemental level essentially one dimensional and sequential, although capable of very high speed will eventually reach limits associated with the RC time constant of circuits which does not scale with miniaturisation. It would seem therefore that computer serial processing speeds in excess of a million million bits/second (1 Terabit/s) will become very expensive.

b. Optical techniques can solve some of these problems because of their intrinsic speed. A separate route to significant increase in processing speed is simultaneously seen through the use of the natural parallelism of optics. This will require new architecture and software but may naturally link with the increasing use of parallel architectures in digital electronic computing. Problems that may be solved are illustrated by the difficulty that existing powerful electronic computers have in image recognition. Other research activities involve concepts of associative memory and the aping of neural networks.

Electronic interconnect capability from one chip to another is limited by the number of connections that it is physically possible to make with an integrated circuit package. Optical interconnects offer parallel interconnection without cross-talk and the possibility of dynamic reconfiguration.

In hardware terms, nonlinear elements can be a new solution to the problem of spatial light modulators with the possible advantages of digital operation, massive parallelism and vastly increased speeds.

The possibility of all-optical computing is much discussed, but it seems much more likely that any practical system will be a hybrid of existing digital electronic methods and the use of optics where clear advantages can be demonstrated. There is no particular virtue in being 'purely optical'. Electronic control of computing steps is convenient and provides a necessary interface with conventional techniques. However, optical control, which can be two-dimensional, additionally offers novel hardware and software possibilities, including adaptive programming.

4.4.3 Status of UK R&D

JOERS support of optical information processing includes a 'Programmable Optical Devices and Spatial Light Modulators' project. British Aerospace, STC and GEC have significant experience in using spatial light modulators for optical processing, Kings College London together with GEC having additional expertise in holographic optical devices. Although there is military interest in target recognition and the problems of radar information processing, the MOD effort is quite small. Another JOERS project in digital optics is targeted at examining the role of hybrid optoelectronic components within digital processing systems used in computing and communications applications. The industrial collaborators are GEC, STC and Plessey coupled with University College London, Imperial College and Cambridge Universities.

In non-linear optics and optical bistability there is an internationally competitive British effort. Giant nonlinearity in III-V semiconductors was discovered and modelled first in the UK. The first optical transistors (transphasors) with gain and usable as a 3-port device followed (1979). This in turn led to the first digital optical circuits. Heriot-Watt University has taken the lead in the European Joint Optical Bistability Project (EJOB) which was the first operation initiated under the EC Stimulation Action. It embraced 8 laboratories in 5 countries and was funded at 1.8M ecu for two years, and was later joined by a further twelve laboratories. The aims of the programme were to define and demonstrate a primitive 'digital optical finite state machine' as well as to conduct appropriate basic research.

US work of significance includes a major effort in 'optical computing' at Bell Laboratories where it is seen as a possible route to a future 'switching computer'. Apart from the substantial evidence of US activity on spatial light modulators, the SDI Signal Processing Consortium comprises some 15 organisations and started with a budget of $9M per annum, Heriot-Watt University being a participant.

4.4.4 Comments

This is a promising area of research with the potential to emerge as a major industrial sector by the turn of the century. The USA and Japan are devoting considerable attention to this field, but the UK is currently well placed with world class research at a number of institutions. We therefore need to maintain our research momentum to ensure that the UK is poised to exploit this technology as the markets emerge.

4.5 Optical storage of information

Storage densities have been doubling every few years since the birth of the computer using core storage and magnetic tape. From time to time, major technological advances occur which revolutionise the market, followed by a period of consolidation; integrated circuit memory components, floppy disc drives and miniature Winchester drives being examples. The next major step-wise function is already underway as optical storage systems are introduced, and the next technological leap will occur when, to interface with parallel processing computer architectures, inherently parallel optical data storage devices are developed.

4.5.1 Data storage requirements

Banking, insurance, retail, manufacturing and other enterprises depend on their survival and expansion on the effective handling of data, using systems provided by the data processing industry.

A key factor in IT is the availability of economical high capacity data storage for storing and retrieving huge volumes of digitized data. The hardware required for data storage is generally the most costly component in the system.

With the introduction of the processing of data involving mixed text, voice, image and graphics, together with intelligent knowledge based systems, the trend for increased storage will accelerate.

The main advantages of optical memory technology can be summarised as:

Greater storage density than magnetic discs or tapes
Reduced physical space
Removable media
Longer archival life than magnetic media
Low cost per stored magabyte
Low cost replication, essential for electronic publishing
Greater security of information in write once memory
No media wear.

4.5.2 Disc storage technology

Optical disc technology, similar to the 'compact disc' used in the music industry, is being developed for use as low cost mass data storage in IT systems. It will be ten times lower in cost per byte than magnetic discs and tape and occupy a tenth of the space. Optical exchangeable discs at or below £0.5/Mbyte may be compared with magnetic exchangeable disc at or above £5/Mbyte. An A4 page requires 0.5Mbyte of storage for a black & white imager, or 3Mbytes with grey scale, both without data compression. Thus a 12cm disc can store the equivalent of 1000 floppy discs or 200,000 pages of A4 text. Very extensive use could be envisaged if the cost can be brought down to 5p/Mbyte as has been suggested.

The technology is based on a laser beam focused on a rotating disc of special sensitive material. There are currently two basic types of optical data storge systems; 'Write Once - Read Many times (WORM)' and 'read only'.

In the 'write once - read many times' system the laser beam is focused on the media surface through a protective cover. The focused beam causes durable pits to be formed. These can be read consecutively using the same focused laser spot at lower power. 'Write once' optical media are user recordable and non-erasable with a storage life in excess of ten years. Capacities of two Gigabytes on a 12" diameter disc and approaching one Gigabyte on a 5 1/4" disc are available. A number of technological alternatives to physical ablation are available to record data in write once systems eg phase changes or evolution of gas in amorphous silicon hydride. The vast storage capacity of this technology allied to the permanence of the data has been used to advantage in markets where indelibility is an asset rather than a liability, notably archiving and recording of financial transactions.

In 'read only' discs the laser beam accesses pre-recorded and replicated data on the media surface. This type of disc is not recordable at the time of use, the data being replicated on the disc from a master before being received by the end user. It is most suited to the distribution of many copies of the same information. The fastest growing implementation of this technology is referred to as Compact Disc Read Only Memory (CD-ROM) and these discs have capacities up to half a Gigabyte on a 5 1/4" dia disc. Applications of the CD-ROM include electronic publishing, parts catalogues, equipment maintenance data and computer software distribution.

A further development of this emerging technology is the 'erasable' or 'rewritable' optical disc. The most developed technology for erasability, at this time, is magneto-optics. Spots on the disc media are heated by a laser beam and, simultaneously, a magnetic field is applied changing the direction of magnetization at these spots. A lower power laser beam is used to read the data on the disc by detecting the effect of the reversal of magnetization on the polarisation angle of the reflected component of the incident read beam. Data is erased or rewritten by again applying the higher-power laser beam and magnetic field, switching the magnetization back to the original direction. Currently favoured magneto-optic materials are amorphous rare earth alloys, but they are barely adequate, having a low signal to noise ratio and possibly poor long-term stability.

The next most favoured technique uses phase transformations induced by laser light. The method depends on the property of certain materials, most notably tellurium oxide alloys, to exist in either crystalline or amorphous states at ambient temperature. The information stored on a disc is again read by a low power laser, and the changes of state induced by use of higher power and different wavelengths. A third method being researched involves a coating of photochromic materials in which reversible changes can be induced as in the other methods. Kodak have announced the availability of an erasable disc in the last quarter of '87 and three or four companies are said to have samples now.

However, the technology is still in the embryo stage, and there is scope for significant improvement in the materials or for radically new technological approaches. There is much activity on a world scale into this technology since it is universally recognised as being the next major breakthrough in IT which will have widespread repercussions well beyond the IT industry itself. The only disclosed activity in the UK brought to the attention of the Working Group is that being conducted by PA Technology in Cambridge in association with Plasmon.

Very large optical disc data storage systems forming automated disc libraries, called 'Jukeboxes' are in development using high speed robotics. These high performance disc handling systems will set new standards for low cost on-line storage, offering capacities of 300 Gigabytes or more, with access times of 6 to 10 seconds. For example, the DHSS could have the full file of any claimant made available to an enquiry officer within a few seconds.

4.5.3 Tape storage technology

Optical tapes has been of interest to at least three UK firms and though currently less fashionable, there may still be a place for these cheaper optical systems in spite of their longer access time. Currently Thorn-EMI are doing research on optical tape recorders with support from DTI. One optical tape cassette should be able to store high resolution (12 pixels/mm) digital images of 4.5 million A4 sheets. That amount of paper would occupy 35 cubic metres or 39,000 times more volume than the cassettes. This is at least ten times more efficient than the best projected digital magnetic tape systems (Video-8, R-DAT). This level of performance would be of interest to market areas such as insurance, financial, legal and medical records. All of these require long term storage and the write-once nature of the recording medium is a security advantage. Other applications include consumer video recorders for High Definition TV; satellite downlink data capture, where a very high recording rate is required; computer back-up; office document storage; engineering drawing files; and seismic and other earth resources data.

4.5.4 Optical cards

For a different area of application, cards similar to plastic credit cards have been developed using an optically sensitive coating rather than a magnetic stripe, or impregnated with a conventional memory chip. Silver halides are the materials currently used with recording and interrogation using laser techniques. Currently, 2MBytes of data can be stored using a standard credit card format, which is equivalent to some 800 pages of A4 text.

4.5.5 Three dimensional storage technology

Long term research is also being directed at three dimensional storage mechanisms using holographic or other similar techniques. These would provide enormous storage potential within minute volumes. The main interest centres on their use in conjunction with optical processing where information would be manipulated and processed in a massively parallel fashion, generating a requirement for similarly massive storage devices capable of operating in novel ways.

4.5.6 National and international issues

Sourcing of optical disc and tape media and drives by IT companies is a key factor in providing more effective IT systems and hence greater success for UK commerce and industry. Internationally there appear to be three major groupings, with no established standards for optical disc viz Philips and Sony, the other Japanese Companies and the US. Experience in videotape standards may make other companies nervous in making too large a commitment before standards are agreed. The attitude of IBM is undisclosed, though they have extensively researched optical systems: any move on their part could precipitate a market for IBM compatible discs.

The most significant development relating to the possibility of a widely accepted industry standard emerging arises from two announcements in the US at the end of 1986. Microsoft, who developed the widely used operating system MSDOS, a derivative of which is used by the IBM PC and is effectively the industry standard for microcomputer software, announced that they intended to to develop an extension to MSDOS to support CD-ROM technology. This coincided with the announcement of the successful conclusion of an agreement by thirteen companies on a standard for CD-ROM discs. This opens the way for the development of products to a standard format to permit the interchange of the software, particularly the discs, and create user confidence that they will not be locked into a single supplier.

Outside professional markets for data storage, there may be markets for compact magneto-optic storage technology to compete with magnetic tape for audio and video recording. Sanyo already have a demonstration system for audio. This may catalyse a merging of professional and domestic markets for optical discs with a single system being used for data, image, audio and video.

Europe in general is poorly placed with regard to optical storage technology. ESPRIT II envisages 200 man-years of research on magneto-optic storage, but outside Philips, it is not clear that there is an adequate base of expertise to justify research on that scale. The greatest need for innovation is in read-write optical storage. Access to optical disc technology is important to the IT industry as well as the entertainment industry.

4.5.7 Comments

The dependence on non-UK sources raises the important issues of strategic availability, balance of trade and UK industry at risk from 'technology transfer' controls. This vulnerable position could be improved by encouraging a UK initiative for this technology. Optical disc technology is still in its infancy and it is therefore not too late for UK companies to enter this market. Such companies would need to be skilled in investing high volume chemical product manufacture for the media and in precision engineering for drives. The UK has established a successful business in manufacture of the audio compact discs (not the players themselves) which should be transferrable to CD-ROM, but this is no substitute for a presence in the 'hardware' arm.

In addition to the need for media and drives a significant investment by IT companies must be made in the system integration of this technology through the development of controllers, systems software and architecture. In the absence of UK investment in optical disc storage technology of any sort, inward investment should be encouraged to establish a UK capability in the manufacture of drives help protect IT business dependent on it.

In the longer term, any moves towards novel three Dimensional storage systems might require such radically different solutions as to offer the UK an avenue to re-enter the information storage market by leaping the current generation.

4.6 Displays

4.6.1 Flat panel displays

Flat Panel Displays can be divided into two classes, emissive, which emit light, and subtractive which reflect, scatter or absorb incident light. There is now only one viable subtractive technology, liquid crystals. The important emissive technologies are plasma gas discharge, vacuum fluorescence, and electroluminescence.

4.6.2 Liquid Crystals

The UK has a long history of invention and production of liquid crystal materials, through the consortium established between RSRE, Hull University, and BDH, and later expanded to include Merck. BDH and Merck now share about 80% of the world sales, most of the remainder being taken by Hoffman La Roche, licensed by MOD. The consortium is still active in research, and is likely to hold its position, though East Germany has developed some new materials and licenses them world wide.

The first liquid crystal display devices were invented in Switzerland, and the US and Japan were quick to exploit them. Japan has now almost eliminated US competition, and has its main rivals in Hong Kong and Singapore. To maintain its market share, it has developed more complex displays, and has exploited newer optical effects in liquid crystals. Europe's main production centre is in the Netherlands, Philips having recently moved their plant from Switzerland. AEG manufactures displays in Ulm. UK production is small, less than £5M per annum, and shared between Racal and English Electric - LUCID.

The UK has been in the vanguard of recent advances in liquid crystal display technology, namely in the development of 'supertwisted' nematic displays, which offer improved contrast and wider viewing angle; and bistable ferroelectric displays which possess the advantage of remaining in a given state until 'switched', and therefore do not require complex thin film transistor driving circuitry. Current research on ferroelectric displays is aimed at reducing the 100-200 volts presently required for addressing. STC have demonstrated a smectic A type display which has excellent contrast and virtually 180 degree viewing angle, but is relatively slow to address. GEC work on active matrices has lead to a new architecture which improves yield greatly. In addition, a new low temperature process for depositing polycrystalline silicon has been developed. Other UK work has resulted in a smectic C type display which can be updated at video rates.

There is clearly a growing demand for liquid crystal displays, and this is matched by a growth in UK industrial research. However, there is strong competition from Japan, which is in a dominant market position.

4.6.3 Emissive Displays

The UK has no manufacturing capability in plasma panels or vacuum fluorescent displays, which currently hold between them about 30% of the market. It is unlikely that this share will grow, because of the technical limitations of these approaches.

Electroluminescent displays have occupied a small share of the market, and the DC powder display was a UK exclusive until Phosphor Products licensed their technology to Cherry. The technology is difficult and may not greatly increase its small market in the long run. Already it is outsold by the AC thin film display, invented and produced in Japan. This technology has many problems, not least of which is the high voltage drive. Nevertheless, the slow growth in sales shows there is a need for new approaches. Pilkingon, Thorn-EMI, and GEC are collaborating to exploit a thin film DC panel invented at RSRE. This is at too early a stage in development to forecast likely sales, but the field is a promising one, and the UK is in a good position to exploit.

4.6.4 Potential Applications

Electronic and electrical systems are made of three parts, the input device, the processing electronics, and the output device. In developing such systems, first principles would suggest that all three parts are critical, and that the chain of system production should not be broken by neglect of one or two links. However, the processing electronics frequently receive the majority of the attention to the neglect of the crucial role of the input and output transducers. Peripherals may lack glamour, but they are very important.

Modern development of electronic and electric instruments, be they oscilloscopes, washing machines, or word processors, is leading to instrument integration, by a process that parallels the circuit integration of ten years ago. The peripherals, particularly the electronic display, now become crucial, partly because they are the human interface, but also because the electronics becomes integral to the display. The neglect of research and development on peripherals is handing over large shares of this market to our competitors.

The field of flat panel displays is a particularly interesting example. Here expertise on the peripheral can determine control over a whole area of the market. The ability to produce personal TV receivers and portable computers is controlled by access to the display. It is no accident that these instruments are virtually the reserve of Japan, because the devices, the flat panels themselves, are made in quantity only there. This move towards market domination is most effective when it is based on the display, since the display is the link with the consumer, the peripheral that forges his impression of the whole system. Europe will always be operating at a disadvantage in the instrument market if it has no local competitive source of displays.

4.6.5 Exploitation

The flat panel display market worldwide is now over £1Bm and increasing by about 6% per annum. There is also a growing market for large area displays for current television formats and a new market will be created for the next generation of high definition television (HDTV) requiring resolutions of greater than 1000 lines.

4.6.6 Non-flat panel displays

Large projected imagery will have increasing appeal. Three technologies are currently competing for this market; one is the large area flat screen display described above; a second is the familiar cathode ray tube, which may be increased to screen sizes of 1.5 metres; the third is optoelectronic image projection. Emissive style projection displays function by virtue of a large number of pixels composed of the three primary colours, creating an extremely complex task of control in real time to display moving pictures without delay or shadowing effects, allied to the need to distribute significant power for illumination. Transmissive or reflective style projection systems in the main use a white light source (or sources) linked to an array of filters and gates to create the required image. The logical extension for the use of such devices is for them to be mounted on the ceiling of a room and used to project 'wall-to-wall' television.

Various other non-flat panel displays already exist, eg head-up and holographic displays, or may be developed in response to perceived needs for imaging, 3-D television etc. They tend to be based either on current flat panel displays or are at such an early stage that it is not possible to speculate on their form.

4.6.7 Comments

The fragmenting of UK effort, as described earlier, has hindered exploitation. This is particularly regretable since device inventions are now beginning to come from UK industry. The fluorescent liquid crystal display, for example, carries the advantages of liquid crystal devices with the attractive appearance of a vacuum fluorescent display. This is a Cinderella field, now abandoned by the Ministry of Defence, who nurtured most of the early work, on the grounds that defence requirements can be met from civil production. The outstanding UK liquid crystal materials work prospered when the research teams were co-ordinated by a single project management team.

High definition television (HDTV) will become a major growth market in the early 1990s, and several UK companies have a substantial interest. This prize is a major one since HDTV has a great potential for domestic, professional and educational applications.

The UK will need to concentrate its efforts on selected markets in order to capitalise on its skills.

4.7 Imaging

Optoelectronic imagers convert optical images into electrical signals, which can then be transmitted, electronically processed, recorded and displayed. Television is the most obvious examples: it was the invention of optoelectronic TV cameras in the 1920s that first made TV practicable.

Recently, visible imagers have seen significant reductions in price. This has led to such products as home TV cameras and portable camera/recorders (camcorders), and also opens the way for a massive expansion in computer vision. Vision will become a primary means by which computers acquire information, just as vision is already the most important means by which the human brain acquires information. Computer vision systems will revolutionise robots and will have a dramatic effect on the way in which humans interact with computers - the man-machine-interface. For this reason computer vision forms a major area within the current UK Alvey programme on information technology.

Optoelectronic imaging extends beyond the visible spectrum into the infra-red region, detecting images which are invisible to the human eye. Light is composed of photons, bundles of energy travelling at the speed of light. Visible light is generated by very hot objects, such as the sun, and the energy within visible photons is sufficient to stimulate chemical changes in the retina of the eye, enabling the light to be seen. Colder objects also emit photons, but these 'thermal' photons have less energy and cannot be seen. Nevertheless they can be detected by material whose properties have been specially tailored for the purpose. Since everything on earth emits thermal photons continuously, thermal imagers can see equally well by night as by day. But because most terrestrial objects have about the same temperature, thermal imagers need to be sensitive to very small temperature differences, and this has made them sophisticated and expensive if television quality imagery is to be achieved.

Only in a handful of civil applications is it yet cost-effective to use high quality thermal imaging: in medical research to locate warm skin patches that may indicate circulatory disorders, by the fire services to see through smoke, by rescue workers to find survivors under rubble, by safety inspectors to find faults in aircraft and industrial plants, which show up as hot spots. At present the major use of thermal imagers is for defence, although for the future, the civilian market is potentially very large.

4.7.1 Vacuum tube imagers

Until recently all optoelectronic imaging has been based on vacuum tubes. The most important of these optoelectronic tubes is the vidicon, in which the optical image illuminates a photoconductor or pyroelectric layer on the front of the tube and a scanned electron-beam reads off the resulting electrical pattern. In a photoconductive vidicon the individual photons generate charges in the photoconductor which make it transiently conducting. A pattern of conductivity builds up across the photoconductor layer, and this pattern is detected by the scanning electron beam. Pyroelectric layers on the other hand are sensitive to heat independent of the wavelength of the individual photons. As a result pyroelectric vidicons can detect both visible and infra-red. Both photoconductive and pyroelectric vidicons can be used to generate TV imagery, but photoconductive vidicons give much better picture quality and pyroelectric vidicons are only used in the infra-red region. English Electric Valve (EEV) has a large and growing market in pyroelectric vidicons.

A second important class of tube is the image intensifier in which the visual signal is detected by an illuminated photocathode. Photons colliding with this layer cause electrons to be emitted, and the resulting pattern of currents can then be electronically intensified. In this way it is possible to produce imagery from very low light levels, as on a moonless night. Military night vision systems using the new gallium arsenide photocathode image intensifier tubes are currently being purchased on a scale of many hundreds of millions of pounds per annum worldwide, particularly in the USA. In the UK, EEV has a world leading technology in this area.

4.7.2 Solid-state imagers for the visible spectrum

The optoelectronic imaging tube is now being overtaken by solid state imaging arrays. These generate more precise images and possess the key advantages of smaller size and weight. Solid state also implies the potential for lower cost, and the possibility of integrating electronic processing directly into the array.

Visible region solid-state imagers, based on a type of silicon integrated circuit known as a charge-coupled-device (CCD) array, have long since achieved TV broadcast quality comparable to tubes. The spur to their development in the last few years has come from the emergence of the consumer camcorder market, where size, weight and cost are crucial. Also important in the future will be the markets for high definition television and computer vision: these markets are spurring research on larger arrays with sizes greater than 500x500 elements.

In a CCD imager array the incident photons generate charge in the silicon integrated circuit. Each element of the CCD array has a metal-oxide-silicon (MOS) capacitor which traps the charge in its vicinity. When sufficient charge has accumulated the packets of charge at each element are readout. This is accomplished by repeatedly passing the charge packets from each element to its next neighbour nearer to the edge of the array, eventually enabling all the packets to be passed to detectors on the edge of the array. The name charge-coupled device signifies this ability to couple charge packets from each element to its neighbour.

In addition to CCDs, other solid state imaging sensors have been developed which use different readout modes. In the future it may be possible to fabricate solid state image intensifiers using III-V superlattice technology. Also important for computer vision and robotic applications is the ability to form a 3-dimensional image. Various techniques can be used to achieve this, including binocular vision and motion cues, both of which are used by the human brain, and optical radar using a semiconductor laser in a pulsed mode.

4.7.3 Solid-state infra-red imaging

Four wavelength bands in the infra-red spectrum can be used for imaging, the near infra-red at about 1 micron wavelength, another band at 2-2.5 microns, and the two thermal bands at 3-5 microns and 8-14 microns. Outside these bands the earth's atmosphere is highly absorbing.

Infra-red solid state detectors, like tubes, can either detect the photons directly, using photoconductors or photodiodes, or instead detect the radiation as heat. For heat detection one can use the pyroelectric effect or other physical phenomena which are very sensitive to temperature. One such technique of current interest uses the phase transition in a liquid crystal to convert the infra-red heat image into an optical pattern in the liquid crystal layer which can then be read optically.

For detecting infra-red photons directly, various semiconductor materials have been used. Significant materials include extrinsic silicon, lead sulphide, lead selenide and indium antimonide, but particularly important for both the 3-5 micron and 8-14 micron bands is cadmium-mercury-telluride (CMT).

For TV quality imagery, CMT thermal imagers employ a simple CMT detector array with a small number of elements and sequentially scan the image across the array using a system of moving mirrors. To give sufficient sensitivity the detector has to be cooled to the temperature of liquid nitrogen (-196 degrees Celcius). Scanning and cryogenic cooling are major factors in the high cost of thermal imagers, and the major goal of present research is therefore to produce more complex CMT arrays, with 128x128 elements and more, which avoid the need for scanning and which are also capable of working with only thermoelectric cooling. But the technology of such CMT arrays is difficult. The detector array is generally made as a hybrid with the CMT detector elements bonded onto a silicon read-out circuit, requiring thousands of faultless bonds between CMT and silicon. Secondly, CMT is a difficult material to produce with the ultra-uniformity required to detect the very small temperature variations in an infra-red image. It is only by sophisticated electronic correction of the array's non-uniformity that good quality imagery can be obtained, and these correction electronics in turn demand state of the art VLSI technology. For these reasons it is likely that TV-quality thermal imagers using CMT will remain solely a military technology for the next decade.

A promising alternative technique uses pyroelectric ceramics deposited on, or bonded to, the silicon readout circuit. Such imagers operate at room temperature and have adequate sensitivity for some military and many civil applications. This approach, being pursued in the USA and in the UK, offers a good chance of low cost thermal imaging.

4.7.4 Optical image processing

Over the past 20 years a great deal of research has been devoted, particularly in the US, to optical image processing. This was encouraged by the fact that optical processing could in principle provide massive computation power of the scale required for image processing and by the fact that the input data was already in optical form. However this research has so far been largely unexploited. Partly this is due to the cost and size of many optical processing systems, but also perhaps to the fact that computer vision requires a great deal of non-linear processing with complex data feedback, and this is difficult to control with analogue optical systems.

Digital optical computers may be able to handle this non-linear processing more effectively. Alternatively radically new concepts such as neural network machines which mimic the architecture of the human brain and require multitudinous interconnections may be needed; light is well suited for this because myriads of light beams can pass through one another without interference. Optical processing of information is described in more detail in section 4.4.

4.7.5 Optoelectronic image projection

Most image projectors currently being developed have as their core element a liquid crystal layer. The image is written into this layer electrically and the resulting optical image is projected. The write operation is achieved either by sandwiching the liquid crystal with a photoconductor scanned with a laser beam or illuminated by a CRT image, or alternatively by sandwiching the liquid crystal within a silicon wafer with an array of CCD or MOS addressing circuitry. Such devices are not only important for image projection but also for optical signal processing, as discussed in section 4.4.

A more detailed discussion of all aspects of display technology, the natural complement of imaging, has already been given in section 4.6.

4.7.6 Opportunities for UK industry

Among UK companies, GEC has the strongest overall position in optoelectronic imaging. GEC components (EEV) has a well established reputation in the imaging tube market, dating from the early years of broadcast television, and in solid state cameras. GEC also has an expanding world business in pyroelectric infra-red imagers for fire fighting and rescue, and in CCDs and image intensifiers for security. Plessey is developing solid state thermal imagers based on pyroelectric ceramics and silicon integrated circuits. Mullard has a large civil market in solid state pyroelectric detectors used in burglar alarms and security systems. British Aerospace has research on CCD imagers with automatic exposure control. Other major European companies in CCD imagers include Philips and Thomson-CSF. The main R&D effort worldwide, however, is in Japan and the USA, aimed at large imager arrays exploiting the Japanese and US capability in mass-production VLSI.

The computer vision market is also expected to expand rapidly, exceeding a billion pounds per annum worldwide by 1992. This could provide a good opportunity for UK industry with a mix of optoelectronic sensor capability and pattern processing/machine intelligence. The latter field has been strengthened in the UK by the Alvey Programme and more recently by the DTI National Electronics Research Initiative on Pattern Recognition. This is an area where there can be good civil benefit from defence R&D.

The UK has a leading world position in CMT thermal imagers deriving from the defence R&D funding over the past 15 years, and outstanding research, notably at RSRE. UK imagers are produced as two classes of common modules, which can flexibly satisfy the full range of defence applications. The smaller modules, suitable for hand-held use, are manufactured by Thorn-EMI: the larger modules, which give the highest performance, are manufactured by GEC-Avionics. Mullard manufactures the detectors and Hymatics manufacturers the detector coolers.

4.7.7 Conclusions

Imaging will become an increasingly important area as exploitation of existing advanced research migrates to low cost, mass produced consumer products. Much of the UK's current strength is in technologically sophisticated high added-value products, particularly for military systems. This is an important capability. Based on this defence technology the UK is well placed to expand in some professional and consumer fields exploiting machine vision and infra-red and thermal imaging. Security is one expanding market. The use of thermal imaging in medicine and in safety and inspection may have significant benefit to the quality of life and have quite a widespread impact on better design and reliability, giving major financial savings.

In the consumer arena the UK is much less competitive. Solid state cameras and camcorders are likely to be a significant consumer product. High definition television, optical storage, personal information systems, video-telephones and other developments over the next decade are likely to enhance the consumer and professional demand for imaging products for recording and projecting all forms of information. Based on present trends this could lead to a major UK balance of payments deficit in this sector in the 1990's.

4.8 Sensors

A sensor, or transducer is a device which produces a variable output in response to a particular input parameter. Most sensors currently are mechanical, electrical, electronic or a combination of such, but in the future, optoelectronic devices will become more prevalent.

Optoelectronic sensors may be divided into two broad groups. Active devices comprise a light source, a pathway containing the element to be sensed, an optical manipulating element defining quantities such as wavelength or path of the light, and a detector. Passive sensors have no explicit light source. The combination of the availability of customised microelectronic chips and the steady miniaturisation of optoelectronic sensors is creating substantial opportunities for novel applications across a variety of industries.

The advantages of optoelectronic sensors are perceived to be primarily technical. They possess high immunity to electromagnetic radiation, intrinsic safety, potential for non-invasive measurement, inherent reliability and are potentially lighter and more compact than alternative options.

4.8.1 Active devices

Gas sensors, including environmental pollution monitoring, eg automobile exhaust gases (carbon monoxide and oxides of nitrogen), fluoro-carbons, etc, are the most prominent examples of active devices. Optoelectronic sensing of carbon dioxide is also widespread and ranges from diving operations in the North Sea, nuclear power stations, greenhouses for enhanced horticultural efficiency, the brewing industry and the intelligent control of central heating and ventilation systems in buildings. All these tasks can be tackled more effectively by a new generation of infra-red interference filter gas sensors. Sufficient potential exists for miniaturisation and unit cost reduction that thousands of individual monitoring points reporting to a central control can be contemplated.

Fire protection is approached in two ways - flame sensing using infra-red passive detectors together with sophisticated signal processing; and flammable hydrocarbon detection with an infra-red interference filter device. The latter, currently under development, is capable of 'fail-to-safety' operation, unlike the commonly used catalytic resistive sensors in general use and which can be poisoned thus 'failing to danger'. This example shows one advantage of optoelectronic sensing devices in general. A further notable application of this class of device is the sensing of alcohol in breath and is currently in use by a number of police forces.

Optoelectronic sensors are also prevalent in the medical and biological fields in such devices as automated gas chromatographs involving miniature spectrometers. Liquid analysis is represented by devices such as the infra-red milk analyser. In the power industry tunable infra-red semiconductor diode lasers are used for monitoring ammonia concentration in power station combustion processes. Other applications extend to process control including such diverse areas as the measurement of thickness of sausage skins, the boring of precise holes in teats for babies bottles, and thickness measurements of materials.

Another significant development in sensor technology is based on extremely small micromachined silicon structures which can be designed to measure various parameters of interest to the process control industry. Although originally developed as a basis for electronic sensors, recent work has indicated that these tiny silicon structures can be applied to optoelectronic sensing.

Remote sensing using laser scattering to cover entire plants has also been the subject R&D activity in recent years.

4.8.2 Passive devices

Passive devices mainly take the form of optical fibre sensors, which may be either discrete or distributed. The former are sometimes described as extrinsic sensors (because the sensing is achieved after launching light from the optical fibre), and the latter as intrinsic sensors, in which changes in the light propagating characteristics of the fibre are detected. Single-mode optical fibre is often used for intrinsic sensors (necessarily for those incorporating interferometric detection schemes), whereas multimode fibre offers the lowest cost implementation of extrinsic sensors. In either case, the properties of light which can be modulated by the measurand are intensity, phase, polarisation and frequency (as in Doppler effects) or wavelength (as in large changes of colour).

In all these cases, low-cost components ar required to complete the optical circuit. Couplers are particularly important, with controlled and environmentally stable characteristics being required.

Research is currently directed at finding more physical properties to which optical fibres may be made selectively sensitive, and to improved detection and quantification of those properties. New themes surround enhancement of wavelength modulation and detection techniques, and balanced intensity sensors. The latter overcome the problem of optical sensors utilising intensity variations, arising from baseline movement when the characteristics of the optical fibre transmission system change, for example by the insertion of an additional connector. One solution is to mix two light signals modulated at different frequencies in such a way that a ratiometric detection scheme can effectively remove all perturbations other than that caused by the measurand in the sensor itself. The balanced sensor arrangement arising from this can be likened simplistically to a fibreoptic version of the Wheatstone bridge. Another method is to develop fibreoptic sensors which modulate the frequency of the light source according to changes in the measurand, overcoming dependence on the intensity of the light source and providing an output readily compatible with digital electronic processing techniques.

As with active sensors, chemical analysis provides a special opportunity for a new range of applications. In telecommunications technology, the drive towards longer wavelengths provides the clue that the losses in silica fibre are minimised at a wavelength of around 1.55 micron, and for fluoride fibres at longer wavelengths. Power transmission through optical fibres uses a wavelength of 10.6 micron derived from a carbon dioxide laser. At wavelengths below this limit, many common chemical compounds show optical activity. This may be inherent, as in vibrational absorption of gases, or indirect as in the change in colour of an indicator immobilised at the end of an optical fibre. A spectrophotometer can therefore be conceived, operating with its sampling system being remote and on-line, perhaps also with the output from several sensor heads being multiplexed together and subsequently resolved using integrated optics techniques.

More speculatively, distributed or integrated sensors may be developed by immobilizing optically active materials on optical fibres, sensing through interaction with the evanescent field which is present outside the light-guiding structure.

4.8.3 Safety

Optical systems are intrinsically safer than electrical techniques for use in hazardous environments, with certification authorities currently assessing the appropriate requirements applicable to optoelectronic systems. Research has concentrated on assessing the possibility that light might be focused to a critical energy density and considering the ignition of flammable atmospheres by small heated bodies (the logic being that focused light might heat a body above a critical temperature). The power levels involved are close to the maximum that can currently be launched conveniently into an optical fibre, so that there is unlikely to be an immediate problem except for higher powered systems.

4.8.4 Standards

The issue of standards is particularly important if optoelectronic sensors are to be exploited because of the nature of the market. Successful systems depend on the integration of many components which in the case of sensors, may often have been developed by companies specialising in the measurement of a particular physical property rather than optoelectronic systems. The sensor must therefore be able to communicate with a potentially very complex control system, possibly via a multiplexed data highway. Standards to facilitate these interconnections are highly developed in the electronics field, but virtually non-existent in the optical domain.

4.8.5 UK position

There are a large number of UK companies, large and small, actively engaged in the development of fibreoptic sensors and instruments. Both SERC and DTI are funding programmes on sensors and instrumentation. In addition, DTI is supporting two industry-led collaborative R&D ventures, the Optical Sensors Collaborative Association (OSCA) and the Optical Sensors Research Unit (OSRU) based at the University of Manchester Institute for Science and Technology (UMIST). Through membership of these clubs, companies can participate in pre-competitive R&D into enabling technologies with the goal of subsequent product development.

UK Universities have been unusually competitive in this field with strong groups at Southampton, Glasgow and UCL. The field of special fibres for sensors and active devices has been pioneered by Southampton University. The Southampton Group has spawned a successful start up company in York Technology, which has achieved a world position in specialist test equipment and components for fibres; and is also unusual among UK Universities in that it has established a vertically integrated technology for fibre and has been able to operate more akin to a Research Institute than most UK departments, having at least one full time senior researcher with no teaching responsibilities.

All Universities face difficult problems in such a fast moving field in maintaining an adequate technology and skill base. This is increasingly being acheived through strategic alliances between Departments within the same or several Universities and between University and Industry.

Some of the most advanced fibreoptic sensor technology has been developed with MoD funding for hydrophones and gyroscopes. Particle sensing techniques using laser scattering have been developed by Malvern Instruments and RSRE, with significant potential in biological and biochemical analysis. This MoD sponsorship has given a number of UK companies a strong capability in the underlying technology which needs to be harnessed as effectively as possible to develop associated civil applications.

4.8.6 International comparisons

The USA represents some 70% of the world market for sensors, and therefore has a dominant position. However, Japan has shown itself to be extremely foresighted with regard to optoelectronic sensors, and has a major demonstration project at an oil refinery of the Nippon Mining Company which has been totally instrumented with fibreoptic devices. Thus, it has been estimated that Japan has about a four year lead over the UK, and probably the rest of Europe also.

4.8.7 Comments

There are excellent prospects for the development of advanced sensors in practically every sphere of human activity. To date, the potential of optoelectronic devices has only been very slightly exposed. The subject has scope for much ingenuity and relatively small scale R&D and it is therefore worth encouraging in the UK context.

The market for optoelectronic sensors is expanding, but there is no doubt that the pace of commercialisation is slower than was originally expected. There are exceptions, however, as in the use of optical sensors to undertake measurements not previously practicable because of the severity of the environment. Examples include vibration and temperature measurement in electricity generating equipment. Applications in the medical and aerospace markets (eg diagnostic kits and gyroscopes respectively) consummate many of the technical advantages of fibreoptics technology and can be foreseen as the technology leaders.

The future of fibreoptics in the industrial market certainly extends well beyond the use of optical fibre as a digital communications link. The major fields of application will be in sensing pressure, temperature, flow, level, displacement etc, but there is a need for more attention to be directed towards novel applications such as chemical sensing. There is a substantial demand for improved measurement techniques applied specifically to areas such as gas detection (methane and other flammable gases, carbon monoxide, toxic gases and pollutants), dissolved chemical species, and biosensing.

The scale of the sensor manufacture in the UK is probably only of the order of tens of millions of pounds per annum. However, these devices are the components of systems certainly worth many hundreds of millions of pounds per annum. The UK industrial sector which provides the impetus for the development of improved sensors, ie industrial measurement and control is highly fragmented. There is a need for co-ordination to identify lucrative future markets and areas of special interest to the UK, with important opportunities for collaboration amongst manufacturers and between suppliers and users. The UK has a solid base of R&D in sensor technology, but needs to devote more resources into the development of commercial products to capitalise on this strength.

4.9 Lasers

There is a large variety of types of laser, of which the eight most significant are carbon dioxide (CO_2), solid state (mostly neodymium YAG and neodymium glass), ion, semiconductor diode, helium neon (HeNe), dye, excimer and helium cadmium (HeCd). They vary in price from $5 (semiconductor diode) to $0.5M (high power CO_2). Table 4.9 gives the distribution of commercial laser sales.

TABLE 4.9
WORLDWIDE COMMERCIAL LASER DEVICE SALES BY TYPE
(in millions of dollars)

Laser Type	1986	1987 (estimated)	
Carbon dioxide	110	121	
Solid-state	85	94	
Ion	86	100	
Diode	121	134	
He-Ne	44	50	
Dye	31	36	
Excimer	19	22	
He-Cd	6	6	
TOTAL	$502M	$562M	(all figures rounded)

(Source: Laser Focus)

Of the non-military applications of lasers Figure 9 shows that the three most significant areas in economic terms are materials processing, research & development, optical memories and medicine; followed by communications. In comparison, the military market in 1986 was estimated at $80M for laser devices and $600M for the total value of the systems into which they were installed (Lasers and Applications: January 1986).

NON-MILITARY APPLICATIONS OF LASERS

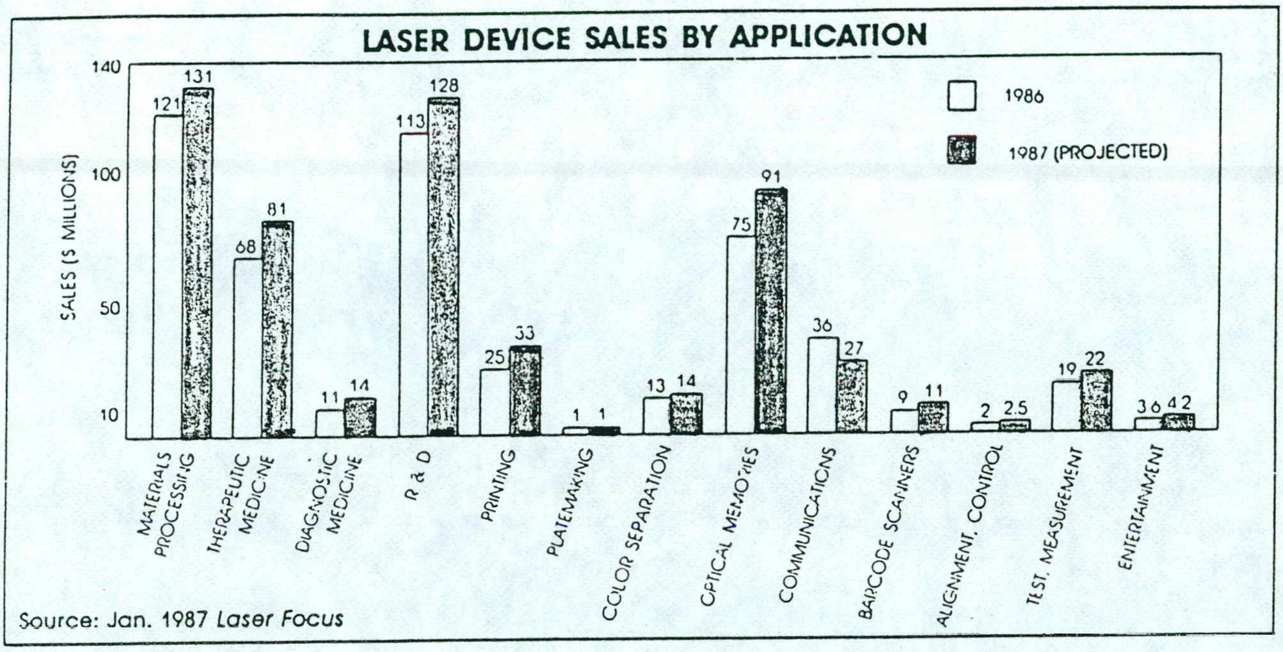

FIGURE 9

Until recently, the single dominant laser type in cash terms was the carbon dioxide (CO_2), used primarily for conversion of electrical power to radiation. It comes in many varieties from kilowatts of continuous power for metal cutting, through gigawatt devices (in short pulses) to small portable 5W devices. The industrial sector is the largest user (45%) with, apart from cutting and welding, marking in the electronics industry, and food and drug packaging as significant areas. As CO_2 lasers become more compact, they are increasingly being introduced into machine tool systems. The medical market for CO_2 lasers is also strong in surgery: gynaecology, dermatology, ear, nose and throat, and in plastic and reconstructive surgery. Further expansion is restricted by the absence of infra-red optical fibres capable of delivering the significant amounts of power required.

The most prominent solid state laser is the neodymium in yttrium aluminium garnet (Nd:YAG) type having a wavelength of 1.06 micron which finds its biggest application in materials processing and medicine; in the latter the capability of optical fibre delivery is important. Military application of Nd:YAG lasers is of approximately equal scale in ranging and target marking etc.

Both CO_2 and solid state lasers are produced in the UK in some numbers: the order of magnitude of the business being about £10M for each type.

Ion lasers find that their largest use in printing where the argon ion is dominant although it suffers from very low efficiency (0.1%). In medicine, biomedical cell sorting is a fast growing application including testing for AIDS. The UK and Europe account for a negligible proportion of the worldwide production of ion lasers, but tens of millions of pounds' worth are imported each year for use in R&D.

Semiconductor diode is the fastest growing laser type. In terms of volume, some 95% are destined for the optical memories market, primarily for audio compact disc players, sales of which could exceed three million in 1987. In terms of value, the major share of the market for diode lasers is in optical communications. Diode lasers are also used in non-impact printing, 85,000 in 1986 predicted to grow to a million units per annum by 1990. Japanese companies are reaping most of the benefits in this growth area. UK presence is dominated by STC and Plessey with a total production of £20M. The growth of mass produced optical storage devices, eg compact disc players will be the driving force behind the development of low cost semiconductor laser diodes.

Helium neon (He-Ne) are low power visible wavelength lasers used to provide portable alignment beams, for bar code readers and in the non-impact printing market for high-speed medium volume copiers. Entertainment applications are also growing rapidly.

Dye lasers are mostly to be found in scientific R&D where they provide variable wavelength sources.

Excimer lasers provide ultra-violet radiation. The applications are shifting away from an R&D base towards semiconductor processing with the possibility of applications in medicine for correction of short sight. The UK has good technology but weak exploitation, the world leaders being Lambda Physik in Germany (now owned by Coherent Inc of the US) and Lumonics in Canada.

The final significant laser is helium cadmium of which 35% are used in printing applications. These are almost all manufactured in Japan.

4.9.1 Civil R&D based on the lasing source

It is important to note the distinction between R&D devoted to the creation of new laser types and R&D concerned with the use and application of lasers.

SERC support of the development of new lasers is divided between the Science and the Engineering Boards, and amounts to about £200K per annum. The remaining civil research largely is located in universities; Heriot-Watt, Oxford, Southampton and St Andrews being most notable, generally all pursuing research into different laser types, but with some limited overlap.

4.9.2 R&D focused on civil applications

UK university and industrial R&D using lasers is by comparison much more extensive, though there is an increasing dependency on the USA for the supply of the lasers themselves.

The largest civil R&D programme is the Central Laser Facility at the SERC's Rutherford Appleton Laboratory, funded at a level of approximately a million pounds per annum. The main purpose of this facility is research in plasma physics using a 1KJ 30 picosecond neodymium glass laser. This together with similar types of laser have been supplied mainly from overseas.

The UKAEA Culham laboratory has developed a number of CO_2 lasers for machining applications which have been licensed to Ferranti. They have also developed various workstations including a robot controlled laser-beam delivery system.

The EUREKA initiative has espoused the EUROLASER project. This is mainly concerned with high-power lasers for industrial purposes; a proposal led in the UK by the Welding Institute is currently at the definition stage. EUROLASER also aims to consider Nd:YAG and excimer lasers.

4.9.3 Defence R&D

Defence R&D on lasers has been concentrated on waveguide CO_2 lasers where internationally competitive technology for ceramic tube long-life sealed lasers was developed at RSRE and Ferranti. In addition, competitive pulsed TEA CO_2 lasers have been developed by MoD establishments in collaboration with GEC Marconi. Military YAG systems now in service were successfully developed for ranging and target marking, the added value of which can be up to ten times the cost of the actual lasers.

4.9.4 General R&D position

The UK's relative position internationally in laser R&D is perhaps best indicated by the historical perspective: the first (ruby) laser originated in the USA in 1960, the helium neon (USA 1961), CO_2 (USA 1964), Nd:YAG (USA 1962), TEA CO_2 (Canada and France 1969), waveguide CO_2 (USA 1970), excimer (USA/Germany 1975). There has been competent British work on a number of these lasers, for example in the mid sixties initial work was done on argon-ion lasers and on far-infra-red rotational molecular lasers.

4.9.5 Production

The worldwide market for lasers as components or sub-assemblies stood at approximately $500 million in 1986, split roughly 40% USA, 25% Europe and 25% Japan (Laser Focus). Military sales are in the region of $70 million per annum. Historically, annual growth rates have been around 20%. The laser manufacturing industry worldwide is dominated by North America, Europe overall having a negative trade balance with the rest of the world. An extreme example is the argon-ion laser, where probably $30M worth are bought and less than $1m worth produced.

No European-owned laser company is in the first 13 companies internationally. Two successful European companies Lambda Physik (world excimer laser leader) and JK Lasers (Nd:YAG and ruby) have been bought respectively by Coherent (USA) and Lumonics (Canada) in recent years.

Major UK laser manufacturers include Ferranti, STC, GEC, Plessey and Barr & Stroud (Pilkington). There is also a thriving small business sector including companies such as Edinburgh Instruments, Laser Applications, Oxford Lasers, Scientifica-Cook, Spectron Laser Systems and Vuman Lasers. The total UK manufacturing effort adds up to sales of about £50m of which some £15m relates to US subsidiaries. Annual UK import and export figures for lasers and systems are reported at £18.4m (mainly ion lasers) and £20.0m (mainly YAG and CO_2 for materials processing) respectively. The import figure understates the true position since it does not include lasers in systems, eg printers, compact disks, etc.

4.9.6 Comments

Lasers are significant because they are a crucial component in a variety of optoelectronic systems which are worth many times the value of the lasers themselves. Worldwide sales of these systems are expected to exceed $11 billion (1986).

The UK is generally weak in research, development and production of non-semiconductor lasers, especially when compared to semiconductor types. This position in the provision of a fundmental component for optoelectronic systems is analogous to the lack of availability of local sources for microelectronic circuit components. This is generally true of the whole laser industry in the UK, with the possible exception of some areas with military applications.

The industry is not so mature that the position could not be corrected. Public procurement in military, telecoms and R&D sectors could be coordinated to stimulate the UK market. Laser science is fast moving with new devices appearing every year so that future trends could be influenced. Consistent with experience in the USA, most new opportunities have been seized by the smaller companies. Measures to assist small companies in this area could help to stimulate additional R&D. Almost exclusively it is the large companies which benefit most from defence procurement, but small companies could be helped if the results of MoD R&D, where appropriate, were made widely available on reasonable terms to act as an important liberating influence and to induce competition.

UK manufacturing industry has been slow to take up laser manufacturing techniques, translating into a small home market for UK laser companies which compares unfavourably with Germany, France or Italy. Laser manufacturers in this sector are therefore heavily dependent on export markets.

Stimulation of opportunities for the application of lasers in the home market is therefore extremely desirable. However, financing of civil R&D is a problem facing both large and small companies. University research on lasers is at a extremely low level and compares unfavourably with activity amongst our overseas competitors; eg, in West Germany there are two Max-Planck Institutes devoted to basic and applied laser work respectively as well as the university programme. Investment in this area of research could lead to new products quite rapidly.

Outside the special major programme at the Rutherford Appleton Laboratory, UK laser effort has been very modestly funded. There are good technical positions in both the civil and military applications of CO2 lasers. Semiconductor laser technology is sufficiently good for the UK to be able to capitalise on large scale future opportunities. Coordination of requirements in the UK across the spectrum of communications, military, R&D, medicine, etc together with measures usable in small companies, as well as large, is urgently required and could provide the basis for exploiting future opportunities. Failure to provide laser components must adversely influence UK manufacturing opportunities in optoelectronic systems generally.

5. GOVERNMENT ACTIVITIES

Government activities in optoelectronics come under the sponsorship of the Department of Trade and Industry. The Ministry of Defence and Department of Education and Science also have major financial and policy interests. The Department of Employment through the Manpower Services Commission are involved with responsibility for the skilled manpower requirements of the nation.

5.1 JOERS and FOS

The major sponsorship activies of the Department of Trade and Industry for the optoelectronics sector have been discharged via the Joint Optoelectronics Research Scheme (JOERS) and Fibreoptic and Optoelectronic Scheme (FOS). The former scheme was designed to stimulate research and the latter to encourage exploitation.

5.1.1 JOERS

The Joint OptoElectronics Research Scheme (JOERS) was the first pre-competitive collaborative research scheme to be launched by the Department of Trade and Industry (DTI) in December 1982. Its aims were to focus more research attention onto optoelectronics.

Initially the Scheme was planned to run for five years and cost in total £25M, of which the DTI would provide £10M, industry £10M and the Science and Engineering Research Council (SERC) £5M. However because of its enthusiastic reception by the Research Community it soon became apparent that the funds envisaged for the five years would be committed in three and were not adequate for the volume of high grade projects submitted for support. In 1986 further funding by DTI and SERC totalling £6.75M was allocated for the years up to 1989. The overall budget is therefore currently £36.2M, £7.25M from SERC, £14.5M from DTI and £14.5M from industry, all of which is now committed.

Although additional funding was made available in July 1986, the Assessment Committee was forced to concentrate its resources within a limited field whilst still continuing to struggle with difficult selection decisions arising from a wealth of promising proposals.

The history of the Scheme to date indicates that it has had a very positive effect on stimulating additional work on a wide range of important topics in optoelectronics. This combined with the much greater degree of collaboration between the industrial partners and universities has greatly strengthened the UK's overall capability in this area, and opened up greater opportunities to commercially exploit the extensive base of expertise.

Further details of the scheme together with a list of projects supported are given in Appendix B.

5.1.2 FOS

The Fibre Optics and Optoelectronics Scheme (FOS) was a programme to stimulate novel product development and capital investment in the UK optoelectronics industry. FOS was launched in July 1981 with £25M allocated by DTI. The take-up was so fast that funds were subsequently extended in 2 stages to about £55M. Of this approximately £38M was committed towards project costs of £190M. FOS has stimulated the development of the industry to the extent that the UK's overall industrial performance in this area is surpassed only by the USA and Japan.

Further details of the scheme are given in Appendix C.

5.2 JOERS/ALVEY

The Alvey Programme was launched in 1983 as a five-year programme to advance UK expertise in information technology, in particular advanced computing systems commonly referred to as 'fifth generation' systems. One of the major themes of the programme, 'man-machine interface' included research into novel display systems, which had a degree of commonality with the objectives of JOERS and FOS described in the preceeding section.

These overlapping interests were therefore dealt with by a joint JOERS and Alvey initiative encompassing the displays aspects of the Alvey man-machine interface programme. Four projects to the value of a total of £12m have been supported under this arrangement with the majority of funding coming from industry and DTI, but additional amounts from SERC and MoD via RSRE.

The four projects are:

- A4-size silicon matrix liquid crystal display
- interactive dc-powered electroluminescent display
- large size storage display based on ferro-electric liquid crystals
- thin film electroluminescent flat panel display

Prototypes of some of the results of these projects have been demonstrated in public and it is hoped that products will be appearing on the market shortly.

5.3 LINK

In December 1986, the Government launched an initiative called LINK, aimed at speeding up the development of products and services arising out of research conducted by universities, Government departments and industry. Through this initiative, Government will support up to half the cost of collaborative programmes between the scientific community and industry. All government departments that have a significant research and development programme are involved.

The Government's contribution will reach £210M over the next five years; overall the initiative will generate expenditure by government and industry of at least £420M over five years, provided industry matches government funding.

The first five LINK programme areas were announced in February 1988. These are molecular electronics, advanced semiconductor materials, industrial measurement systems, eukaryotic genetic engineering and nanotechnology. Up to £83 million will be spent on these five programmes, of which the Government will provide half. LINK will expand to include further programmes, ranging across the entire spectrum of science and technology: it is hoped that, amongst others, further programmes will include optoelectronic materials, digital optoelectronic processing, advanced manufacturing technology, medical electronics, engineering materials and subsea communications.

Further details are given in Appendix D.

5.4 Other DTI activities

Outside of JOERS, FOS, LINK and the Alvey Programme, details of which are discussed in preceding sections, the Department of Trade and Industry (DTI) have a number of general schemes to support research and development in industry under which assistance for optoelectronic projects has been given and is still available. These are described in more detail in Appendix E.

5.4.1 Industrial Research Establishments

Of the DTI's four industrial research establishments, two have relevant optoelectronic programmes which are described below.

5.4.1.1 National Engineering Laboratory (NEL)

NEL began its involvement with optoelectronics through a research and development programme in computer vision in 1979. Subsequently, the optoelectronics group of NEL's Metrology section was integrated into the computer vision group to complement their existing programme of R&D activity and introduce new techniques and devices to image analysis. In addition to the design and development of new optical sensors, the optoelectronics group has also been investigating the application of optical contouring techniques to three dimensional component shape determination, thereby extending the capabilities of computer vision systems beyond two-dimensional image analysis.

5.4.1.2 National Physical Laboratory (NPL)

The National Physical Laboratory (NPL) forms the apex of the National Measurement System. NPL maintains and organises the dissemination at the highest level of the nation's measurement standards, carries out R&D to meet evolving and likely future measurement needs, and provides related measurement and advisory services.

Optoelectronics poses particularly difficult problems in the measurement field. Firstly, it throws up requirements for many new or significantly extended measurement techniques. For example, optical fibre and integrated-optic devices demand measurements of waveguiding properties that were previously only associated with microwave or longer wavelengths, while some optical and optoelectronic devices require characterisation on unprecedently short time scales. Secondly, technological change is rapid, so that the development of measurement techniques and standards - by its nature a painstaking process - is stretched to keep pace.

NPL has well-established capabilities in fields that relate directly to optoelectronics, such as lasers, optics, and optical, infra-red, electrical and micro-dimensional measurement.

Since 1983, NPL has been working on measurement standards for fibreoptics, covering in particular the properties of radiation sources and detectors, and optical fibres used mainly in telecommunications. NPL is now one of the leading national standards laboratories in this field. Techniques and standards for the generation and precise measurement of optical and electrical pulses on picosecond time scales are also being developed.

During the next five years it is expected that most of the optoelectronics 'pull' on NPL for new techniques and standards will remain in fibreoptics, with an increasing share from short distance and non-telecommunications applications. Work is planned on coherent and wavelength-multiplexed optical transmission (eg laser frequency standards and characterisation of non-linear effects in fibres), connectors, guided-wave junction and terminal devices (eg loss, spectral and polarising characteristics, mode-field characterisation) and special fibres for sensing or other applications.

Over the next decade, increasingly complex forms of integrated-optic and optoelectronic integrated circuit will be developed and will have growing impact in information transmission and processing. In measurement terms, both at research and manufacturing stages, these will create a rich mixture of demands: for example, the reliable characterisation of the multi-function materials which may be used in these devices will be a major task.

In addition to its work on measurement standards, NPL makes a major contribution to the development and support of national and international specification standards for the information technology industry, especially in the field of conformance testing methods. This work will in future need to cover new capabilities of computing/communications systems brought about by developments in optoelectronics. Research involvement in the area is a prerequisite for the development of these future standards.

5.5 Other SERC Activities

Outside of the JOERS programme described in section 5.1, SERC supports research in optics and optoelectronics using its normal procedures through both the Physics Committee of the Science Board and the Information Engineering Committee of the Engineering Board. The Council's total commitment to the JOERS programme is £7.25M over five years. At 1 January 1986 the value of the research grants portfolio, other than JOERS, was approximately £2M from the Physics Committee and £3.4M from the Information Engineering Committee. Since grants are typically of three years duration this implies an expenditure of just under £2M in total per annum outside JOERS.

The sources of funding reflect differences in the nature of the work being supported. The interest of the Physics Committee is in advancing the fundamental understanding of the underlying science. The motivation for such work is not necessarily or exclusively because of its relevance to optoelectronics, but is essential in the long term if work of a more applied nature is to be successful. An identification of funding for optoelectronics cannot therefore be made unambiguously. Nevertheless the figure quoted above provides support for research which includes a major emphasis on quantum, non-linear and solid-state optics as well as a significant interest in atomic spectra and photon interactions; work on optical properties and condensed matter spectroscopy is also supported. Over twenty academic departments are involved. By way of illustration, the Department of Physics and Applied Physics at the University of Strathclyde is very active in studies of laser materials; the Physics Department at Imperial College is studying the theory of non-linear waveguides, the generation of ultrashort pulses and the cooling and trapping of atoms. The School of Electronic Engineering at Bath University is carrying out theoretical studies of the non-linear dynamics of semiconductor lasers. Theoretical quantum optics is particularly active in centres such as Essex University, Imperial College, Strathclyde University, Heriot-Watt University and UMIST.

Engineering applications, supported by the Information Engineering Committee, tend to concentrate on optical materials and devices (especially optical waveguides, fibreoptics and integrated optics), and optical information processing with some support for semiconductor lasers and laser applications as well as for optoelectronics materials and devices. Research sponsored largely through the JOERS programme has led to significant technological developments. For example, there have been very considerable improvements in fabrication techniques for lithium niobate, the base material for monolithically integrated structures and for components of integrated optical systems with potential for advanced instruments such as interferometers and optical switches. There are about ten academic groups actively pursuing applications-orientated research on optoelectronics in the UK, supported partly or mainly by the SERC. They include the Physics Department of Heriot-Watt University which is carrying out research on non-linear materials, theoretical and experimental studies on optically bistable devices, optical circuits, holographic interconnects, computer architecture and on non-linear waveguides. The Department of Electronics and Information Engineering at Southampton University has established a high international reputation for its research on the production and performance of novel optical fibres. That, allied with the expertise in the Physics Department at Southampton in the fundamental understanding of laser physics, has led to very significant advances in the production and use of fibreoptic lasers. The extensive research programme in the Department of Electronic & Electrical Engineering at University College London covers a wide range from the design and fabrication of optoelectronics devices to their integration into optoelectronic systems for applications including sensing and communications.

Both the Science and Engineering Boards also support other activities which may benefit the optoelectronics programme, although not as their primary objective and not included in the funding levels quoted above. Of particular importance are facilities for materials growth and characterisation. The Engineering Board supports facilities for III-V compound semiconductors at Sheffield University which have provided materials support to the programme; the Science Board is developing its Low Dimensional Structures initiative (which the Engineering Board hopes to match with a Low Dimensional Devices initiative of comparable magnitude) which is likely to provide additional materials support.

The Council supports a number of other programmes which relate to optoelectronics in various ways but which are not seen as part of the Council's programme in this field. Examples are research in robot vision systems for manufacturing, conducted as part of the ACME (Applications of Computers to Manufacturing Engineering) initiative, and research in computer vision systems which forms part of the Council's contribution to the Alvey programme.

Mechanisms for the support of research are of two main kinds. JOERS represents a strongly coordinated and collaborative programme in which academic research forms part of a single programme with industry which has clearly defined objectives and associated timescales. Other research in optoelectronics is not constrained to specific programme objectives. Rather, support is determined through the process of peer review as normally practiced by the Council. This is for two main reasons. The first is that the subject as a whole is relatively wide and there must be an opportunity to mobilize support for interesting new areas of research as they arise. The second is that the best speculative ideas from individual researchers ought to be supported to open up previously uncharted areas. However, this does not mean that the programmes lack direction. Both committees keep their programmes under continuing review and apply criteria of selectivity and concentration to try to achieve the optimum value for money in the most important research areas. This has resulted in a tendency for support to be concentrated in a relatively few institutions, especially in the engineering sector, which in many cases are subject to formal biennial review. This is an appropriate response in a field requiring substantial capital expenditure to sustain viable research programmes. Furthermore, in order to maintain coherence between the physics and engineering programmes, cross-membership is maintained between the relevant peer review bodies.

There has been increasing pressure on resources in this field over the last few years, and consequently the Council intends to increase its expenditure in this area. The Information Engineering Committee has experienced a substantial increase in demand, possibly as a consequence of the focus created by JOERS, and intends to increase its spending by an amount rising to £800K pa. The Physics Committee has experienced a more steady rise in demand but is considering the case for an initiative in, and increased funding for, quantum, non-linear and solid state optics. This is expected to include quantum optical studies and the generation and development of novel optical sources, for example new optical non-linear materials, solid state gain media, the generation of ultrashort pulses and semiconductor diode lasers.

5.6 Other MoD activities

Optoelectronics is important in many areas of defence systems. Topics which can be discussed broadly in an unclassified context include sensors, signal processing, communications and displays. Other topics which will not be discussed here include laser rangefinders, active imaging, laser designation, laser weapons and other military laser applications mainly based on Nd:YAG and various gas lasers. Research on optoelectronic devices and subsystems is carried out for all three services at RAE, ARE, RARDE and RSRE.

The sections 5.6.1 to 5.6.4 are restricted to MoD research on optoelectronics technology, but it is worth emphasising that there is much innovation from MoD establishments and UK industry in systems exploiting optoelectronics, eg the leading UK capability in cockpit imaging systems and head-up displays.

5.6.1 Sensors

There is strong MoD R&D on infra-red sensors for night vision and for penetrating smoke and mist. The main infra-red (IR) emphasis is on photoconductive and photovoltaic cadmium mercury telluride (CMT) sensors for the 8-14 micron band and the 3-5 micron band. Current thermal imagers use cryogenically-cooled CMT detectors with mechanical scanning of the image. The SPRITE CMT detector, invented at RSRE, is an important UK contribution in this area, and these detectors together with a well conceived modular approach to thermal imager systems have given the UK a world lead in this area.

Existing imagers are expensive and this limits their scale of use even for military systems, and certainly for civil applications. Current emphasis is on much cheaper thermal imaging systems that can avoid the need for cryogenic temperatures and on the use of staring arrays that avoid mechanical scanning. The integration of the CMT detector material on top of silicon processing electronics is key to making large staring arrays. As array sizes become larger the silicon processing electronics becomes a significant issue.

Pyroelectric systems represent another very important class of thermal detector for defence use. These are cheap and operate at room teperature, but have less sensitivity than cooled CMT detectors. Visible and near-IR imaging is also of defence importance for cheap systems, and is being used for example in vision systems for prototype robotic vehicles. This includes 3-dimensional imaging using scanned laser ranging systems.

Towed fibre-optic sensors have application for submarine detection, either of magnetic signals or of long wavelength wave signals. There has been some MoD funded research on such sensors, although not on a scale comparable with the substantial programmes in the US, notably at Naval Research Laboratory, Washington. Optical fibres are also of use for sensor readout: in the UK, GEC under MoD funding is researching fibreoptic readout of piezo pressure transducers for underwater sensing.

An important area of MoD research is on countermeasures to prevent sensing in the IR and millimetric-wave bands. Smokes, flares and other decoys are obvious examples, but the work has little significance outside the defence field.

5.6.2 Processing

The dominant technology for military processing is digital silicon VLSI. MoD has a small research effort on analogue optical processing, but does not believe the field yet justifies a major programme. There is undoubtedly a military requirement for immense processing power, particularly for such tasks as synthetic aperture radar processing, electronic warfare, command and control, pattern recognition and machine intelligence. However at present optical processing systems are a long way from providing adequate performance. The main problems are lack of dynamic range, high power consumption, high cost, weight and bulk of optical systems and their lack of ruggedness. For very high speed optical processing, light sources, modulators and detectors are required capable of working at frequencies of tens of gigahertz, giving frequency performance substantially higher than silicon ICs and permitting radio frequency processing at microwave and millimetric-wave frequencies.

The largest UK programmes on optical processing are in industry, notably at British Aerospace and GEC. Within MoD establishments one important topic is the acousto-optic spectrum analyser, with work at the Admiralty Research Establishment and in industry. RSRE has a significant team exploring general ideas across a wide field of analogue and digital optical processing, covering non-linear optical materials and digital optical devices (in collaboration with the teams at Heriot-Watt and University College London), the use of fibreoptics for processing, optical signal processing analogs of surface acoustic wave devices (and vica versa), phase conjugation, and devices based on liquid crystals.

RSRE also has a significant programme on neural network machines, now expanded by staff from industry as part of the National Electronics Research Initiative on Pattern Recognition (RIPR). This work is currently based on digital processors, such as the ICL DAP. Work in the USA indicates that optical processing may be well suited to neural network machines. This is partly because these machines use analogue computation and do not require high numerical precision, but also because they require complex connectivity, and the ability of light beams to pass through each other without interaction is particularly significant for achieving very complex connectivity.

Spatial light modulator technology is a crucial element in optical processing. In this area GEC Marconi Research Laboratory has developed a good capability based on initial developments by Hughes Aircraft in the USA, and helped by GEC expertise in liquid crystal device technology derived from their displays work. A spatial light modulator of the Hughes performance currently costs $40K, and substantial cost reduction is needed. For low resolution, LCD displays from Japanese pocket TVs provide a cheap (<£100) capability.

5.6.3 Communications

Fibreoptic communication is of increasing importance for defence. In the late 1970s and early 1980s, MoD sponsored considerable work on optical fibres, couplers, III-V sources and detectors aimed particularly towards optical communications within the Ptarmigan battlefield communications system, optical data buses in aircraft and optical data links to missiles. Data capacity, lightness and strength were important in addition to the intrinsic security of fibeoptic communications. The distinctive defence emphasis was on ruggedness and environmental performance, including nuclear tolerance.

In the event, the Ptarmigan project used conventional copper cable rather than fibreoptics because of the higher risk of the fibreoptic approach. However fibreoptic communications remains very important in the longer term. For example in aircraft, fibreoptics allows much greater freedom in routing the data bus which can greatly improve the flexibility of aircraft design. The use of fibreoptics for carrying phase information for phased array radars has been under research at RSRE, and other requirements have been discussed in the section on imaging technology (4.7). Industrial contracts have been placed with GEC, Plessey and STC concerned with advanced GaAlAs lasers and optical modulators which are particularly in support of this phased array work, although also of general value. STC is undertaking research on high strength fibres and splices for long command links for submarine towed arrays and missile data links.

More speculative research at RSRE includes research on achieving LED and laser action from extrinsic centres in silicon. This work is related to a National Electronics Research Initiative Project centred on RSRE in silicon hybrid assembly (RISH) and aimed at optical communications at the circuit level. Also of interest is light emission from CMT at far infra-red wavelengths. This would be matched to the theoretical optimum in fibre loss and dispersion which should occur at around 5 micron wavelength.

5.6.4 Displays

MoD has been responsible for a great deal of the pioneer display research in the UK through programmes at RSRE and funding in industry. The defence exploitation of this work has been limited however because it turned out to be so difficult to produce displays of the complexity required for many defence applications. Defence has therefore generally continued to use cathode ray tubes, even in environments such as aircraft cockpits, although flat panel plasma displays are used for command and control applications where compactness and ruggedness are important.

MoD funding of displays research, both in industry and within RSRE, has been significantly reduced in recent years, being largely replaced by DTI funding through JOERS and joint DTI-MOD funding though JOERS/Alvey. Recent MoD funding in industry has mainly been in support of RSRE research and the work on liquid crystal materials. BDH continues to dominate the world liquid crystal market through the original MoD patents and the continuing succession of materials improvement and innovation generated during the past decade.

A recent development carried out jointly by RSRE and Laser-Scan is a high resolution large area display exploiting a laser-addressed liquid crystal light valve. This display has military value for command and control, but may also be suitable for many civil applications requiring electronic drawing board and large area display capability. Two recent display developments funded by MoD at STC are concerned with the integration of liquid crystal displays onto silicon addressing circuits. One is a simple sight; the second is a 256x256 display which potentially has substantial commercial applications.

Much of the remaining RSRE displays team is now devoted to JOERS/Alvey projects on liquid crystal and DC electoluminescent displays in collaboration with industry. One recent innovation from RSRE has been the supertwist liquid crystal display, which gives much better field of view for heavily multiplexed displays. The supertwist concept has been exploited strongly by the Japanese and is also being developed by EEV under MoD contact.

5.7 European Programmes

There are five major European industrial research programmes which are relevant to the optoelectronics sector. The first three - ESPRIT, RACE and BRITE - are shared cost programmes, that is, they are part funded by the European Community (EC) and part by industry, involving collaboration between firms, universities and other research establishments across the European Community. The other two programmes - COST and EUREKA - are European rather than EC initiatives and involve more than just the EC member states. COST and EUREKA are not funding mechanisms but rather frameworks under which R&D collaboration can take place.

Further assistance from the European Community which is relevant to optoelectronics comes under the Stimulation programme and the STAR initiative.

5.7.1 ESPRIT

The European Strategic Programme for R&D in IT (ESPRIT) was launched in February 1984 and was conceived as a 10-year programme. ESPRIT aims to encourage collaboration within the European IT sector and make Europe competitive in world IT markets. The first phase from 1984-88 has an overall EC budget of 750 MECU which is now fully committed. The programme has been popular - 204 projects have been approved and the UK is participating in 145 of them. A work programme for a second phase has now been published. EC funding for ESPRIT II is expected to be 1600 MECU.

Specific optoelectronics projects involving UK partners under ESPRIT are described in Appendix F.

5.7.2 RACE

The European Communities programme of R&D in Advanced Communications in Europe (RACE) is aimed at establishing a robust Community manufacturing industry in broadband communications, accelerating the emergence of a strong and competitive Community market for equipment and services and unifying standards. This will be fostered by conducting the pre-competitive research necessary for developing a technology base beyond 1995. The RACE programme commenced in July 1985 with a "definition phase" which was completed in December 1986. This was designed to formulate a reference for integrated broadband communications and to evaluate and explore technology options for R&D to be undertaken under shared cost contracts. The UK has been very successful in the definition phase and of the 32 consortia, UK companies are leaders in 14 and have a presence in 26. Of the 192 participating companies, 52 are British. The current funding allocation is 500 MECU of which approximately 20% is attributable to optoelectronics.

The Commission has proposed a follow-up programme which is yet to be agreed. It is expected that work on long-haul, high bit rate, links may be trimmed since the necessary technology is already available or within view, but that further optoelectronics activity is likely to be directed towards technical problems of the local loop and advanced techniques for mass production.

Specific optoelectronics projects involving UK firms under the definition phase are detailed in Appendix F, and the formal statement of the objectives of the RACE programme is given in Appendix G.

5.7.3 BRITE

The European Communities programme for Basic Research in Industrial Technologies for Europe (BRITE) was launched in March 1985. The programme is aimed at promoting pre-competitive technological research which, although not yet related to the development of marketable products or processes, pursues clear-cut industrial objectives. The purpose of the programme is to bring together complementary research from different countries in collaborative projects which will improve the competitiveness of European industry. The budget is 125 MECU over 1985-88 and may shortly be increased to 185 MECU. 99 projects are being funded in the first round and a further 112 projects will be funded in the second round if the increased budget is approved.

The programme supports cost-shared R&D projects. Opportunities exist for projects to involve optoelectronics within the programme areas of realiability, wear and deterioration, laser technology, joining techniques, testing methods, new materials, and production technologies suitable for products made from flexible materials. There were no specific optoelectronics projects funded in the first phase, but 6 are expected to be funded in the second phase, 3 of which involve UK organisations.

5.7.4 COST

COST (European Co-operation in the field of Scientific and Technical research) is an informal organisation set up by a Ministerial Conference in 1971. There are nineteen participating countries - the twelve EC member states plus Austria, Finland, Norway, Sweden, Switzerland, Turkey and Yugoslavia. The main aim of COST is to promote collaboration in R&D. Countries choose to participate in a particular project if they are already involved at national level in research in the field under consideration (or intend to initiate a national project) and would find it worthwhile to collaborate with other participants.
Participation in projects is voluntary and agreed by signing a Memorandum of Understanding. Additional expenditure is often minimal as the research relating to a particular project is generally already underway. Costs usually relate to co-ordination of activity nationally and attendance at meetings. Proposals in general do not involve the setting up of joint research projects.

There are currently five COST optoelectronics projects and the UK is participating or intends to participate in all of them. These are:

i. COST 215: High bit rate optical fibre

ii. COST 216: Optical switching and routing devices

iii. COST 217: Optical measurement techniques for advanced optical fibre devices and systems

iv. COST 218: Material science and reliability of optical fibres and cables

v. COST 222: Waveguide theory for integrated optics

5.7.5 EUREKA

EUREKA is a framework for promoting collaborative projects in fields of advanced technology which was agreed on 6 November 1985. 19 countries (the 12 EC Member States plus Austria, Finland, Iceland, Norway, Sweden, Switzerland, and Turkey) and the European Commission are now involved. EUREKA projects aim to produce high technology goods, processes and services with potential for profitable sales worldwide, using the European market as a springboard.

Through EUREKA, governments and the European Commission can assist the development and commecial success of collaborative projects in two ways. First, EUREKA provides for a process of information exchange on potential areas for collaboration between firms or organisations in different countries who are either seeking partners for specific projects or expressing an interest in collaboration in certain fields. Second, where a number of firms have agreed upon a EUREKA project, but anticipate a particular barrier to market penetration (eg incompatible standards in different EUREKA countries, or public purchasing restrictions), their governments can on request apply pressure in the appropriate fora for action to resolve the problem.

5.7.6 The Stimulation programme

The objective of the Stimulation programme is to foster high-quality collaborative research between research laboratories in Member States. The current programme, financed at approximately 15 MECU per year is scheduled to continue until 1988, when it will be subsumed within the Framework Programme.

The major activity under this programme of relevance to optoelectronics is the European Joint Optical Bistability project (EJOB) involving 20 laboratories across Europe, led by Heriot-Watt University and has received funding of 1.8 MECU over two years. This was the first action initiated under the Stimulation programme and aims to define and demonstrate a primitive 'digital optical finite state machine', as well as to conduct basic research.

5.7.7 STAR

The STAR programme offered grants of up to 55% towards the establishment of modern telecommunications infrastructures and the supply of advanced services facilitating optimum use of that infrastructure for certain less favoured regions of the European Community.

Although not directed towards R&D, this and similar programmes demonstrate a possible mechanism whereby assistance might be granted for large scale demonstrations of new optoelectronic technologies.

6. EDUCATION AND TRAINING

6.1 Schools

We have been concerned to note the decreasing importance being given in schools to the teaching of 'optics' within the physics curriculum. We are aware of the great pressure from all quarters for increased emphasis on 'their' particular aspect of the discipline, but unless fundamental concepts of 'light' such as transmission, reflection and refraction are taught at GCSE and GCE 'A' level, students will be unable to grasp the application of the technology in later life. **We recommend that the Department of Education and Science review the GCSE National Criteria for Physics with a view to including treatment of the properties of light as a core component of the syllabus.**

We also recommend that optics be included as part of the common core curriculum currently being devised, though at this stage, it will naturally fall within a discussion of the broader role of science and technology within the curriculum.

We recommend that a basic understanding of the potential of optoelectronics should be included alongside electronics in subsidiary curricula on the basis that in the course of the working lives of those currently undergoing secondary education, optoelectronics will be comparable in importance to 'pure' electronics. There are now available relatively inexpensive educational kits to illustrate the fundamental principles of optoelectronics which schools could be encouraged to purchase.

For GCE 'A' levels, similarly **we recommend that the GCE Boards and the Secondary Education Council review their treatment of optoelectronics within their science syllabuses.** The demonstrator project in section 2.2 would assist in achieving this goal by providing useful educational equipment.

6.2 Universities and polytechnics

At undergraduate level, pressures on the syllabus have led to less emphasis on optics in physics courses. We recognise that lately this trend has been reversing, but we believe that further emphasis should be placed on optics and optoelectronics in first degree engineering courses. We were encouraged to learn that many Electrical/Electronic Engineering Departments already have optoelectronic modules and in some cases complete courses on optoeletronics. We would welcome expansion of these activities.

At post-graduate level, much is already being done to educate and train in optoelectronics and we encourage those centres to continue expanding their valuable work.

We welcome the significant interchange of personnel between universities and polytechnics and industry, and the numerous other initiatives such as PICK-UP and JUPITER designed to promote awareness and technology and technology transfer. We would wish to see such initiatives increase, with optoelectronics being given the high profile we believe it warrants.

A specialist area in which the UK does lack essential expertise is in micro-mechanical engineering. The miniaturisation of electronics has brought about an associated requirement for precision engineering on a minute scale. The UK's weakness in this area is demonstrable in the lack of UK manufacturing penetration in magnetic disk and tape storage mechanisms in computer, audio and video markets. Optoelectronic devices will place an even greater premium on these skills with no foreseeable improvement in the supply of such skills on the horizon. **We therefore recommend that the University Grants Committee, the Committee of Vice-Chancellors and Principals, the Scottish Education Department and the National Advisory Body for Polytchnics consider measures to strengthen UK activity in micro-mechanical engineering.**

6.3 Vocational training

With regard to technician and craft level training, optoelectronics systems are not sufficiently widely deployed as yet for there to be any major problems, but we believe that the UK must remain vigilant to avoid a repetition of the widespread shortages which have occurred in electronics skills. **We therefore recommend that the BTech, City and Guilds and Engineering Industry Training Board review their programmes to ensure that adequate courses and training places are available to meet the needs of industry as optoelectronic systems become more common.**

At Chartered Engineer level, the Engineering Institutions themselves need to adapt to the changing environment. The historic divisions between the institutions are already under strain as new disciplines such as software engineering, information engineering and computer integrated manufacturing span traditional boundaries of mechanical, electrical and production engineering. The Institutions have already gone some way towards this with, for example in the amalgamation of the Institution of Electrical Engineers and the Institution of Electronic and Radio Engineers, but the structure is in need of more co-ordination to take into account the changing environment in engineering where electronics, computing and manufacturing technology are now all pervasive, to be followed in time by optoelectronics.

6.4 External advice

ACARD, in proffering its advice on the 1984 Green Paper "The Development of Higher Education into the 1990s" (10) stressed the need to raise the skill base of the nation and amongst other things, called for a higher education system more flexible and responsive to the needs of employers and recommended a single national body to advise government on the totality of education requirements. The Report of the committee under chairmanship of Lord Croham (8) in reviewing the working of the University Grants Committee proposed the establishment of a United Kingdom Education Commission to advise Government and educational institutions on national needs in relation to the educational system. We have noted that the White Paper on Higher Education (9) rejects these and other calls for an external advisory body on education.

The final report of the Information Technology Advisory Panel ITAP (subsumed within ACARD and now ACOST) "Learning to live with IT" (7) also recommended that a Commission of Enquiry be appointed but in this case with a remit to consider the educational system needed for the next century.

We have not discovered a convincing reply to these well reasoned cases and therefore **we recommend that the government reconsider these calls for the establishment of a mechanism to bring to bear external advice, especially an industry voice, to the educational system.**

7. COMMENT

From the preceeding sections common themes have emerged in a number of places which merit discussion in a broader context. These are conveniently grouped under the headings of materials, machinery, manpower, money and markets.

The conclusions from the whole report and recommendations are then presented in section 2 which, for convenience, is placed at the beginning of the report.

7.1 Materials

As with all engineering endeavour, Figure 8 illustrates that the roots of a radical change in technology are found in the underlying materials science. The UK has a sound base in optoelectronic materials, but cannot expect to be able to pursue all promising avenues of research on its own, nor can it afford the luxury of a multiplicity of centres following similar research themes. Nationally co-ordinated initiatives are required, with UK companies pooling their resources and in some cases adopting European wide collaboration for the most speculative lines of research, or those requiring large scale investment. At present, no body exists which is capable of exerting the necessary influence to achieve this co-ordination.

In this respect, it was gratifying that in discussions and evidence received from overseas sources, existing collaborative initiatives in the UK were highly regarded. In particular, the user clubs stimulated by the Alvey programme were much admired as an example of industry co-operation, as was the Optical Sensors Collaborative Association (OSCA). It is worthy of note that in both these cases, as in the Centre for Science and Technology, the Government's role as catalyst is equally or more important than its role as financial underwriter.

7.2 Machinery

Whatever the success of our R&D activity, the resulting products have to be manufactured in sufficient quantity at the right price with the high level of quality required in today's markets.

Over the last decade, the UK has witnessed an overall decline in its manufacturing sector, a trend which is now hopefully showing signs of reversal. The skills required for manufacturing optoelectronic devices have much in common with electronics, namely ultra-pure starting materials, mass production techniques and micromechanical engineering. To be successful in this chain, all the links must be in place. The Japanese are the prime example of international prowess in this realm, and in UK trade missions and exchanges with Japan, the UK needs to concentrate more on what it can learn from Japan, possibly licensing some of their technology, rather than advertising the excellence of our scientific research and offering it free to anyone prepared to listen.

7.3 Manpower

Manpower will always be a limiting factor for any new technology which by definition will not have an existing pool of labour with the requisite skills at all of the required levels of expertise. The education system needs to be broadly based and dynamic to respond to the changing needs of society and the working environment. Over the last decade, industry has had to adapt to the new environment of unprecedented technological change. It has been painful. Now the education sector must respond to this challenge also. The need to be at ease with the technology extends from the clerk whose day-to-day work will bring him or her face to face with the information technology revolution, through the maintenance technician who has to repair the equipment when it goes wrong, to the research scientist working on the underlying principles for the next generation of products.

There are currently a wealth of reports and proposals for changes in the field of education and training. These can be summarised as a desire to strengthen links at an establishment level between schools and their surrounding businesses, between universities and industry; and a need for a central focus at all levels of education and training to enable the employers of the products of the system to exercise some influence in what potential recruits are taught.

7.4 Money

Optoelectronics, as presented throughout the report is bristling with exciting new opportunities. Clearly, the UK cannot pursue all of these with equal vigour: we must be selective. What has emerged however, is the scale of expenditure required to remain in the game, and the strenous efforts being made by governments and industry overseas to ensure they stay at the table. This extends from long term speculative research to large scale demonstrators. In comparison with our major industrial rivals, we are not committing sufficient resources to remain in the running.

French Government sources quoted expenditure in the region of £50M for the early Biarritz experiment which involved the installation of a broadband multimode fibreoptic network supporting 1500 videophone terminals in domestic subscriber premises. The follow-up programme - Plan Cable - which has now been frozen at its current projections, will cost in the region of £300M per year over approximately 5 years to provide a mixed co-axial/fibreoptic network serving a potential market of two million subscribers.

In the Federal Republic of Germany, the Ministry for Research and Technology had spent the equivalent of £90M up to the end of 1985 on the development of optoelectronic components and in addition £80M on trial projects in optical communications. The Ministry currently has a budget of £90M for research on components for optical communications systems and this expenditure is in addition to significant support from the regional 'Lander' administrations.

These sums dwarf the amount of Government assistance available for all optoelectronics in the UK through JOERS (£22M over 5 years), FOS (£38M over 6 years) and even the total amount available under LINK (£210M over 5 years), only a small fraction of which will be devoted to optoelectronics.

European governments thus put a high priority on the telecommunications sector as important in its own right, but also as a stimulus to their domestic optoelectronics industries. This is simplified by direct government control of telecommunications. In the UK, our private sector telecommunications industry has to balance R&D expenditure and infrastructure investment against short term commercial objectives in the context of uncertainty in the overall government policy towards the industry.

In the USA, precise figures for government support for optoelectronics research are not available, but of the $1000M spent annually by the Federal government on civil R&D in information technology, a significant proportion will be spent on optoelectronics (though even this is dwarfed by military expenditure).

The Japanese characteristically have a totally different approach. Recognising the strategic importance of this new branch of technology, in July 1980 the Optoelectronic Industry Technology and Development Association (OITDA) was formed by eleven leading companies under the guidance of the Ministry for International Trade and Industry (MITI). OITDA had 225 supporting companies by the end of 1985 and engages in research, standardisation, feasibility studies, system development and public information. The UK has a similar organisation - the Optical Sensors Collaborative Association (OSCA) - operating in a small sector of the optoelectronics market, and another successful example operating on a much larger scale and across the whole of an industrial sector in the Chemical Industries Association.

In optoelectronics, the UK falls between all of these approaches. It does not have the same level of government financial support enjoyed by our European partners, the level of defence funding and coherent market size of the USA, nor the industrial co-ordination and domestic market size of the Japanese. However, we could learn from all these examples, and the recommendations of the group are framed with this objective in mind.

7.5 Markets

Through many of the market sections of the report in Chapter 3, a common theme is the need for a coherent internal European market free from artificial barriers, to match the size of the USA and Japanese markets. We therefore encourage the UK Government to continue its pressure for the removal of barriers to trade and maintain the momentum towards completing the internal market structure of the European Community by 1991.

For individual market sectors, the matrix analysis in Figure 7 highlights the UK's strong position in communications, computing and defence. The relatively large market sizes for these sectors suggest that the UK should be well placed in world markets. Aerospace is the other sector where the UK has a wide technology base allied to a reasonably sized market.

One vital issue which has become clear is the strategic importance of optical data storage, and the dismal position of the UK in this technology and its market opportunities, save in research on some of the materials involved. The proposed industry association will need to consider action to remedy this situation as an urgent priority.

To remain competitive on a world scale, the UK will have to look increasingly to collaboration. Collaboration in research is most effective when it is based on a position of parity or strength. Commercial collaboration is most effective when you have something worthwhile to trade. A weak partner cannot negotiate a good deal and rarely profits from it. Within Europe the UK has an inherent advantage in that most projects with a large number of participants (especially true of ESPRIT and RACE) have to use English as their main working language, being the only one common to all members. This ought to provide the UK with a dominant role in European collaborative ventures which we ought to exploit through a better co-ordinated approach.

To prosper, UK companies will need also to establish alliances with overseas companies outside government and EC programmes for collaborative R&D in common areas of interest, exchange of research in complementary areas, and for rapid access to foreign markets. More use could be made of EUREKA, and it is hoped that collaboration in defence R&D and procurement will prosper through the Independent European Programme Group (IEPG) and bilateral arrangements. This latter issue of European collaboration in defence R&D and production will also be addressed by the ACOST working groups studying defence R&D and international R&D.

Thus, by focusing on our strengths, the UK should be able to negotiate favourable terms to gain access to overseas markets and those technologies which we choose not to develop ourselves. However, this should be a positive conscious strategy, ideally co-ordinated through the proposed Optoelectronics Industry Association, rather than left to chance!

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APPENDIX A

ORGANISATIONS VISITED OR WHICH SUBMITTED EVIDENCE TO THE WORKING GROUP

Barr & Stroud Ltd
British Aerospace plc
British Embassies in Bonn, Paris, Tokyo and Washington
British Petroleum Company plc
British Telecom Research Laboratories
Brown Boveri Kent plc
BT&D Technologies Ltd
Centre National d'Etudes des Telecommunications
Chemical Industries Association
CGE Alcatel
Direction Generale des Telecommunications
Edinburgh Instruments Ltd
EETPU Cudham Hall Training Centre
GEC Hirst Research Centre
Heriot Watt University Department of Physics
Imperial College of Science & Technology Computing Department
Institute of Physics Optical Group
Institution of Electrical Engineers
Lucas Research Centre
Ministere de la Recherche et de l'Enseignement Superieur
National Engineering Laboratory
National Health Service Procurement Directorate
National Physical Laboratory
Optical Sensors Collaborative Association
Philips
Phosphor Consultants
Pilkington Medical Systems Ltd
Plessey Research Caswell
Racal-Chubb Ltd
Royal Signals and Radar Establishment
Secondary Examinations Council

Societe Anonyme des Telecommunications

STC Technology Ltd

Thompson CSF

Thorn-EMI

University College Department of Electronic and Electrical Engineering

University of Southampton Department of Electronics & Information Engineering

York Technology Ltd

APPENDIX B

THE JOINT OPTOELECTRONICS RESEARCH SCHEME

B1. The Joint OptoElectronics Research Scheme (JOERS) was the first pre-competitive collaborative research scheme to be launched by the Department of Trade and Industry (DTI) in December 1982. Its aims were to focus more research attention onto optoelectronics and to:

- Encourage medium to long-term collaborative R&D
- Stimulate 'pre-competitive research'
- Encourage industry/academic cooperation
- Stimulate inter and intra-university interaction
- Maximise exploitation of the results by UK industry
- Bring about greater awareness of the potential of the topic area
- Build up an identified community in the topic area

B2. The Scheme is overseen by the JOERS Assessment Committee (JAC) which draws its membership from academia, industry and the Ministry of Defence (MoD). The JAC is responsible for the selection and monitoring of support given under JOERS. The JAC appoints a Project Asessor, normally a member of the Committee, who on its behalf assesses the project before the Committee considers support, and often for those projects which are supported, monitors their progress. The JAC reviews projects after the first six months and normally at yearly intervals thereafter. It is also charged with detecting and filling critical gaps in UK activity in the optoelectronics field through direction of its funds where appropriate.

B3. Projects under the Scheme are undertaken jointly by industry and university laboratories. Such collaborative activities are normally at the early "pre-competitive" stage of research when the combined interests of several industrial laboratories and academic departments can be focussed on particular topics within the overall field of optoelectronics. In this context optoelectronics has been defined as solid state technologies and devices involving photons in their operation.

B4. This includes topics such as:

- Integrated optoelectronics
- Integrated optics
- Fibreoptics components and systems
- Display technology
- Sensors
- Data storage
- Novel materials
- Langmuir Blodgett films
- Optoelectronic materials

B5. Because of the accent on the collaborative and long-term nature of such projects, the Department of Trade and Industry (DTI) offers grant of up to 50% of costs incurred in industry, while the Science and Engineering Research Council (SERC) gives 100% support to complementary equivalent effort in universities. All UK companies with an interest and R&D activities in optoelectronics are eligible, though the advanced technological topics addressed, and the resources required in skilled manpower and advanced equipment has meant that most interest for the Scheme has come from the major companies.

B6. In addition to collaboration in the projects, exchange of findings between participants in the Scheme is encouraged through group activities on particular topics such as III-V materials.

B7. From the outset of the Scheme it was recognised that to maximise exploitation of the results by UK manufacturing industry it was important that the industrial property rights should reside with the industrial companies involved. Thus the JOERS rules require all the IPR resulting from projects to be transferred to the industrial companies and protected by them as they consider necessary. The industrial collaborators in specific projects grant each other a royalty-free licence to use respective foreground information and patents to exploit the results of the project and a licence on fair and reasonable terms to use their respective background information and patents for the same purpose. Where the industrial collaborators do not themselves sufficiently exploit the results of a specific piece of work, they will be required to grant licences to do so to other participants in JOERS on fair and reasonable terms.

B8. A list of projects supported under JOERS is given below:

- Lithium niobate for integrated optics
- Long wavelength optical fibres
- Base technology for semiconductor waveguide optics
- Theory and technology of quantum wells in semiconductors for optoelectronic applications
- MOCVD growth and assessment of InP based optoelectronic materials
- Langmuir-Blodgett and related polymer films for optoelectronics
- MBE growth of III-V materials for advanced optoelectronics technology
- Anisotropic fluorophosphors for electro-optic displays
- Components for coherent optical systems
- Programmable all-optical and optoelectronic devices and their applications
- Organic electro-optic and non-linear optical materials
- Polymer optical fibres with low loss transmission
- Alternative inorganic materials for optoelectronics: a study of growth, deposition and characterisation
- Liquid crystal polymers and optical memories
- Optical guiding elements using liquid crystals
- Novel active micro-optic devices
- Advanced measurements on optical fibres

- Advanced optical fibre waveguide devices (2 separate projects)
- Active optical switching and logic
- Sensors
- Advanced assessment for III-V materials
- Digital optics: applications for computing and communications
- Organic electro-optic and non-linear materials
- High performance spatial light modulators
- Integrated optical device technology
- Theory and characterisation of advanced photodetectors
- Integrated optoelectronics base technology
- Advanced MOCVD technology for III-V optoelectronic materials
- Long wavelength fluorophosphors
- Active optical switching

APPENDIX C

THE FIBREOPTIC AND OPTOELECTRONIC SCHEME

C1. The Department of Trade and Industry (DTI) Fibre Optics and Optoelectronics Scheme (FOS) was a programme to stimulate novel product development and capital investment in the UK optoelectronics industry. The original aims were:

- to build up an industrial capability to meet the needs of equipment companies and users of optical fibre system components;

- to build up a UK industrial competence in optoelectronics technologies and to stimulate the supply of components, with particular emphasis on critical components for novel systems;

- to develop an infrastructure supplying materials and equipment to the optoelectronics and optical fibre industries;

- to stimulate novel applications by means of public and private-sector procurement.

C2. Around 150 projects were supported, ranging from small company start-up projects to large research and capital investment programmes within Memoranda of Understanding. 60 companies were involved. Support was provided under the standard terms of Support for Innovation (SFI) - now discontinued - or Section 8 of the Industry Act as appropriate.

C3. The UK now has :

- four major optical fibre manufacturers; Optical Fibres Ltd (BICC/Corning), GEC Optical Fibres, Pirelli and STC, which together produce as much fibre (over 300,000 km in 1986) as the rest of Europe put together;

- two manufacturers of world stature, STC and Plessey, of advanced optoelectronic components, including very high bit rate long wavelength semiconductor lasers and receivers;

- a world leading manufacturer of undersea fibreoptic communications systems, STC Submarine Systems. This company's recent achievements include the world's first international submarine optical fibre cable, UK-Belgium 5, and a $350M order for the supply of the world's first private fibreoptic transatlantic system, PTAT1;

- a leading manufacturer of solid state CCD imagers, English Electric Valve (EEV);

- an infrastructure of both large and small specialist companies supplying advanced fibreoptic instrumentation and manufacturing equipment, including Heathway, Special Gas, York Technology, Vickers Instruments, STC, Cossor, BICC and Task.

APPENDIX D

LINK

D1. Government departments participating in LINK are the Department of Trade and Industry, Department of Education and Science, Ministry of Defence, Department of Energy, Department of the Environment, Department of Transport, Department of Health and Social Security and the Ministry of Agriculture, Fisheries and Food. Other departments including the Scottish Office, the Northern Ireland Office and the Welsh Office, will also participate as appropriate. The scientific input to LINK projects comes mainly from the Research Councils and from higher education in which a considerable proportion of LINK expenditure will be invested.

D2. In due course, LINK will consist of a range of programmes, each in a strategic area of science and technology, with the primary objectives of:

- fostering strategic areas of scientific research directed towards the development of innovative products, processes and services by industry;

- stimulating a real increase in industry's own investment in R&D;

- helping industry to exploit developments in science and making scientists more aware of industry's needs by strengthening the links between industry, higher education, the Research Councils and other research establishments;

- developing technoligies which cross the boundaries of industrial sectors and scientific disciplines.

D3. LINK has a steering committee of industrialists, government officials, representatives of the academic community and the Research Councils, chaired by Mr Robert Malpas, a managing director of BP.

APPENDIX E

OTHER DEPARTMENT OF TRADE AND INDUSTRY SUPPORT SCHEMES

E1. The Enterprise Initiative

In January 1988, the DTI launched the Enterprise Initiative, which brings together the services provided by the Department for industry and commerce. The Enterprise Initiative redefined the DTI's role in encouraging innovation, emphasising precompetitive research and collaborative projects. Thus the general scheme for providing innovation grant assistance to individual companies was ended, save in exceptional cases which offer significant national benefits. Some categories of small firm are also still eligible for innovation grant assistance.

E2. SMART

Having noted the Small Business Innovation Research Scheme sponsored by the National Science Foundation in the USA, in 1986 DTI launched an experimental scheme entitled SMART (Small Firms Merit Award for Research and Technology) to encourage small firms and would-be entrepreneurs to develop new ideas. Initially, 20 awards worth £37,500 each were made available for projects in the realm of biotechnology or instrumentation, the latter category encompassing significant opportunities for optoelectronics. The best ten ideas received development grants each worth up to £50,000 (50% of allowable costs). The experiment was successful and SMART is being expanded to make available up to 100 awards. The scope of the technologies now comprises all those covered by the DTI.

E3. Research initiatives

In 1986, DTI announced a new approach to encourage advanced research, the first being in electronics and called the National Electronics Research Initiative (NERI). It is envisaged that these research initiatives will enable pre-competitive industrial collaborators to work together on a single site specially chosen for its existing facilities and expertise.

The first two initiatives involving pattern recognition and silicon microsystems will be based at the Royal Signals and Radar Establishment (RSRE) at Malvern, and the third on silicon architectures will be hosted by Edinburgh University. It is envisaged that further collaborative research initiatives will be developed, possibly in pattern recognition, advanced semiconductors, molecular electronics and microsystems, offering opportunities for further advancement of research, including optoelectronics, based on existing centres of expertise.

The research initiatives are fixed term activities at one location pursuing a specific topic, with research staff assigned by the participating companies or organisations. The definition and direction of the research programme are agreed between these partners who have free access to the resulting intellectual property. It is intended that through this mechanism new topics where companies may be deploying a small effort, particularly in longer term research, can gain significantly through scale, interaction and improved facilities if the research is pursued through a research initiative. By bringing together a larger number of researchers to form a critical mass the UK will have an opportunity to pursue new research activities more effectively in world terms. Expolitation of the products or processes will be the responsibility of the partners, either separately or in joint ventures.

MOD and SERC are also actively involved in supporting these initiatives.

E4. Related DTI initatives

DTI has many related activities in materials, electronics and computing, some of which although at present not including any optoelectronic content, may do so at a future date. In particular, £25M has been set aside for support of UK users and manufacturers of gallium arsenide integrated circuits. The aim is to encourage early exploitation of the material in projects which will build on the substantial research base already in existence in the UK. The initiative has been planned for 3 years' duration and is restricted to electronic applications, but there is no essential reason why, if it were successful, it could not be extended to cover optoelectronic applications at a later stage.

APPENDIX F

EUROPEAN PROGRAMMES

F1. ESPRIT

Specific optoelectronics projects involving UK partners under ESPRIT are described below:

F1.1 Indium phosphide based optoelectronic circuits

This project aims to increase the data rate in information transmission systems, by the use of high performance devices and a variety of multiplexing techniques, mainly using different wavelengths. Out of twelve partners, three are from the UK.

F1.2 Optical interconnect for VLSI and high bit-rate integrated circuits

This project is investigating the application of optical interconnection to reduce the package pin count and electromagnetic interference in VLSI, high speed integrated circuits, and in sub-assemblies containing these components. Two of the three partners are from the UK.

F1.3 Optical interconnect for VLSI and high bit-rate integrated circuits

This project aims to design, manufacture and evaluate a functional optical interconnect demonstrator working at up to a gigabit per second, demonstrating pin count reductions for VLSI chips, and optimising the physical aspects of optical interconnections. Two of the three partners are from the UK.

F1.4 Molecular engineering for optoelectronics

This project aims to produce novel materials for the fabrication of devices using linear electro-optical effects, second-order frequency mixing effects and third-order effects. There are four partners, one which is from the UK.

F1.5 Large area complex LCDs addressed by thin film silicon transistors

The aim of this project is to investigate a viable technology for the fabrication of large area (A5 to A4) complex (up to 1000 addressable lines) LCDs based on polycrystalline and amorphous silicon transistor active matrices. There are five partners, one of which is from the UK.

F2. RACE

Specific optoelectronics projects involving UK firms under the RACE definition phase are detailed below.

F2.1 Monolithic integrated optoelectronics

This project aims to identify the best strategy for the development of ZnP based integrated optoelectronic circuits for coherent communication systems. There are four partners, one of which is from the UK.

F2.2 Low cost optoelectronic components

This project's objective is to reduce the manufacturing costs of components for broadband communication networks. Out of eight partners, one is from the UK.

F2.3 Integrated optoelectronic PIN FET receivers

This project will examine critical technology issues in achieving an integrated or a monolithic PIN-FET hybrid technology in CMT and GaAs for the application of cheap 280 MHz receivers for the subscriber loop. Out of five partners, one is from the UK.

F2.4 Switching techniques and technologies

This project will evaluate electrical technologies for space and time division multiplexing, and label address switching, together with optical technologies for space switching for applications having channel rates of 2-140 Mbits/s or greater. Three of the eight partners are from the UK.

F2.5 Optical switching technologies

There are two projects. The first one will identify the critical requirements for R&D to meet the needs for single mode switching in trunk and local disribution. One of the four partners is from the UK.

The second project will study the requirements for optical switching to ensure work will lead to advantages over electronic switching. Then it will investigate alternative solutions and carry out a detailed study of pre-selected alternatives. Three of the eight partners are from the UK.

F2.6 Optical components in relation to network architectures

This will postulate novel system architectures and consider the implications for passive components; study the possibilities of low-cost production of such components in optical fibre devices or integrated optics; and identify further R&D necessary for processes which will lead to reduced costs for commonly used optical components. Two of the nine partners are from the UK.

F2.7 Optical fibre and components for broadband switching

This will assess the production compatability of switch and single mode optical fibre technologies for an optically activated directional switch which may be caused to change state using an address which is readily separated from the data travelling through the network. Two of the four partners are from the UK.

F2.8 Polymeric optical switches

This aims to demonstrate the potential of electro-optic polymers for optical switching in the wavelength range 0.8-1.6 microns as an alternative class of material to that of inorganic compounds. The aim is to identify the most promising switch configuration upon which to pursue R&D. Three of the six partners are from the UK.

F2.9 High bit rate long haul optical links in the mid-infra-red region

This will analyse the relative advantages and disadvantages of infra-red (2-3 microns) wavelength transmission for long distance communications. The investigation will include new optical fibre materials such as floride glasses, emitters and detectors. The use of infra-red fibres, crystalline, glass and gas lasers will also be taken into consideration. There are eight partners, one of which is from the UK.

F2.10 Assessment of systems and components for optical telecommunications

The objective of this project is the critical appraisal of technology trends for long distance communications to establish the practical limits on capacity and span of silica-based optical fibre links achieveable within the next 5-10 years, and to identify where further research will have significant medium term benefits. Four of the nine partners are from the UK.

F2.11 Systems techniques and components optimised for the optical subscriber loop

This project will survey current optoelectronic technology and expected trends particularly LED's and passive components for high speed transmission on single mode fibres to develop the technical andeconomic aspects of integrated broadband local networks. There are five partners, one of which is from the UK.

F2.12 Coherent multi-channel techniques for integrated broadband subscriber communication systems

This project will exploit the potential and limitations of coherent multi-channel techniques for subscriber systems with emphasis on low cost, mass production and adaptability to existing ISDN and new services such as HDTV. One of the four partners is from the UK.

APPENDIX G

OBJECTIVES OF THE RACE PROGRAMME

The goal of RACE is to make a major contribution to the "Introduction of Integrated Broadband Communication taking into account the evolving ISDN and national introduction strategies, progressing to Community-wide services by 1995".

The general objectives of RACE are, in this light:

a. to promote the Community's telecommunications industry so as to ensure that it maintains a strong position at European and world levels in a context of rapid technological change;

b. to enable the European network operators to confront under the best possible conditions the technological and service challenges with which they will be faced;

c. to enable a critical minimum number of the Member States of the Community to introduce commercially viable IBC services by 1996;

d. to offer oprotunities to service providers to improve cost-performance and introduce new or enhanced information services which will both earn revenue in their own right and give indispensable support to other productive sectors of the Community;

e. to make available to the final users, at a cost and on a timescale at least as favourable as in other major western countries, the services which will sustain the competitiveness of the European economy over the next decades and contribute to maintaining and creating employment in the Community;

f. To accompany the formation of a Community internal market for all integrated broadband communications related telecommunications equipment and services based on agreed European or international standards as an indispensable basis for sustained strength on the world markets;

g. to contribute to regional development within the Community with the support of the development of common functional specifications for equipment and services permitting the less developed regions to benefit fully from the efforts of Member States piloting the telecommunications developments in the Community.

ABBREVIATIONS

ACARD	Advisory Council for Applied Research and Development
ACME	Applications of Computers to Manufacturing Engineering
ACOST	Advisory Council on Science and Technology
AERE	Atomic Energy Research Establishment
ANSI	American National Standards Institution
ARE	Admiralty Research Establishment
AT&T	American Telegraph and Telephone Company
BBC	British Broadcasting Corporation
BRITE	Basic Research in Industrial Technologies for Europe
BTRL	British Telecom Research Laboratory
CATV	Cable Television
CD	Compact Disc
CD-I	Compact Disc - Interactive
CO2	Carbon dioxide (applied to a type of gas laser)
COST	European Co-operation in Scientific and Technical research
CMT	Cadmium Mercury Telluride
CVD	Chemical Vapour Deposition
DCVD	Directorate for Components, Valves and Devices in Ministry of Defence
DHSS	Department of Health and Social Security
DTI	Department of Trade and Industry
EC	European Community
ECU	European Community Unit of accounting
EDTV	Extended Definition Television
EEV	English Electric Valve subsidiary of GEC
ESPRIT	European Strategic Programme for Information Technology
FOS	Fibreoptic and Optoelectronic Scheme
GaAs	Gallium Arsenide
GCE	General Certificate of Education
GCSE	General Certificate of Secondary Education
HDTV	High Definition Television
IBCN	Integrated Broadband Communications Network
IC	Integrated Circuit
IEPG	Independent European Programme Group
InP	Indium Phosphide
ISDN	Integrated Services Digital Network
IT	Information Technology
JOERS	Joint OptoElectronics Research Scheme
LAN	Local Area Network

LDD	Low Dimensional Devices
LDS	Low Dimensional Structures
LED	Light Emitting Diode
LPE	Liquid Phase Epitaxy
MECU	Million European Community Units of account
MBE	Molecular Beam Epitaxy
MOCVD	Metal Organic Chemical Vapour Deposition
MOD	Ministry of Defence
NATO	North Atlantic Treaty Organisation
Nd:YAG	Neodymium in Yttrium Aluminium Garnet
NTT	Nippon Telephone and Telegraph Company of Japan
OEIC	OptoElectronic Integrated Circuit
OITDA	Optoelectronic Industry and Technology Development Association
OSCA	Optical Sensors Collaborative Association
PIN-FET	P-type Intrinsic N-type Field Effect Transistor
RACE	R&D for Advanced Communications in Europe
RAF	Royal Air Force
RARDE	Royal Armaments Research and Development Establishment
RSRE	Royal Signals and Radar Establishment
SAR	Synthetic Aperture Radar
SDI	Strategic Defence Initiative
SERC	Science and Engineering Research Council
SFI	Support for Innovation Scheme
STC	formerly the Standard Telephones and Cables Company Ltd
TEA	Transversely Excited Amplification
UKAEA	United Kingdom Atomic Energy Authority
VLSI	Very Large Scale Integrated circuit
VPE	Vapour Phase Epitaxy
WORM	Write Once - Read Many times
YAG	Yttrium Aluminium Garnet

GLOSSARY

Analogue	A continuous representation of information which may take any real value.
Camcorder	A combined portable video camera and cassette tape recorder which may also incorporate replay facilities.
Coherent detection	A method of transmission and detection where both transmitter and detector operate at the same frequency to enable a network to support a large number of simultaneous links with their interferring with one another.
Chemical vapour deposition	A method of depositing films of insulating or conducting material onto a wafer.
Cytology	The study of the structure and function of living cells.
Diffusion	A method of modifying the characteristics of a semiconductor material by stimulating the migration of chemical constituents using heat or other means.
Digital	Representation of data by a series of distinct numbers, usually in binary format.
Dopant	A chemical impurity deliberately introduced into a semiconductor material to modify its electrical characteristics.
Electro-optic material	A material which exhibits a change in its optical properties when an electric field is applied
Encryption	The coding of information for transmission or storage to prevent it being read by unauthorised persons.
Epitaxy	The growth of a crystal layer, usually of doped material, having its crystallographic structure aligned to the substrate wafer on which it is grown.

Karyotyping	The identification and classification of parts of the nucleus of living cells.
Molecular beam epitaxy	A technique for depositing highly regular epitaxial layers onto wafers by allowing beams of molecules to impinge at low energy onto the wafer surface.
Micron	One thousandth of a millimetre or millionth of a metre.
Single mode	The use of an optical fibre with a very small core (8 micron diameter) for transmission such that only one path exists for the light to travel down.
Multimode	The use of an optical fibre with a relatively thick core (50 micron diameter) for transmission such that light travelling along the fibre can take a multiplicity of paths.
Non-linear material	A material whose properties change in response to the intensity of light applied to it.
Quantum Well structure	A structure composed of very thin alternate layers of different semiconductor materials, the fundamental properties of which are exploited to produce devices such as lasers, optical modulators and switches.
Semiconductor material	A material with properties between those of an insulator and a conductor. Silicon and Germanium are the most common, but compound material such as Gallium Arsenide (III-V materials) are becoming more important.
Wafer	A thin slice of semiconductor material, currently up to six inches in diameter.
III-V material	A compound composed of elements from groups III and V of the periodic table (which frequently exhibits semiconductor characteristics).