An instrumentation strategy for laser radiation safety assessments

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AN INSTRUMENTATION STRATEGY FOR
LASER RADIATION SAFETY ASSESSMENTS

by

David Corder MEng.

A Doctoral Thesis submitted in partial fulfilment of the requirements for the award of Doctor of Philosophy of Loughborough University.

April 1997

© by D.A. Corder (1997)
This thesis is dedicated to my Mother
and in memory of my Father.
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I would like to thank Dr. John Tyrer and Dr. David Evans for providing the opportunity to complete this research project, and for their guidance and support.

I am grateful to Dr. John Harry, Dr. Rob Roach, Dr. Elizabeth Raymond, Dr. Jon Petzing and Mr John O'Hagan for the advice and assistance provided during this research project, and the technician support from the Electronic and Mechanical Engineering Departments.

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The Maximum Permissible Exposure (MPE) to laser radiation defines a level below which an acute injury will not be sustained. Values for the MPE are defined by international standards, based on research into biological laser damage mechanisms and thresholds. To verify that a given laser installation does not present a hazard it is necessary to compare accessible levels of laser radiation to the MPE. In most cases this can only be done by a combination of measurement and calculation.

The standard presents MPE values as tables of formulae. Users find the standards difficult to interpret and use for practical assessment tasks. It is shown by theoretical analysis and practical investigation that the measurement process is non-trivial. This research has identified that general purpose laser radiation measurement equipment is not capable of undertaking the critical pulsed measurements needed for MPE assessments. These instruments are usually limited to measurements of average power, or pulse energy over a limited range of pulse parameters. Analysis of the standards shows that energy measurement is a critical aspect of the radiation hazard assessment process. During the practical investigation a radiation hazard was demonstrated to exist in many laser displays used for entertainment purposes.

To meet the measurement criteria laid down in the standard a novel detector strategy is developed to provide accurate pulse energy measurement. No single detector can meet these current criteria over the complete laser radiation spectrum. Three types of detector are used to measure the output of all common lasers. This leads to the concept of a modular instrument design, incorporating common detector interfaces with signal conditioning to provide a standard output signal format to an interface unit which extracts the relevant parameters from the data for processing by a palmtop computer. The software guides the user through the measurement process, controls the hardware, determines the measured radiation level from the data, calculates the appropriate MPE and displays the results. Techniques were developed to minimise the occurrence of user errors. This required consideration of human-computer interfacing techniques in the software design and unique coding of each instrument element.
The measurement precision of the instrument was determined using stable laser and light emitting diode sources. A scanned laser display system was then used to determine the measurement precision of the combination of a typical source and the meter. It was found that the instrument precision exceeded that of the source, essential if the instrument measurement results were to be reliable. For safety critical instrumentation, calibration is identified as an important issue. Electrical and optical techniques are discussed.

Alternative applications for the instrument were considered. A technique for high power laser measurement using a beam sampling technique was demonstrated. This had advantages when compared to traditional methods of high power laser measurement. The sampling technique was extended to the construction of a laser beam delivery monitor capable of monitoring beam power and position and shutting off the laser in the event of a fault developing.

Since the completion of the research project the instrument has been developed commercially in collaboration with a UK company. The commercial instrument uses the same strategy, hardware and software designs as developed during the research project.
NOMENCLATURE

a.c. Alternating Current
ACGIH American Conference of Governmental Industrial Hygienists
ADC Analogue to Digital Converter
AEL Accessible Emission Limit
ANSI American National Standards Institute
BS British Standard
CDRH Centre for Devices and Radiological Health
CEN Comité Européen de Normalisation
(European Committee for Standardisation)
CENELEC Comité Européen de Normalisation Electrotechnique
(European Committee for Electrotechnical Standardisation)
CIE Commission Internationale de l'Éclairage
CO₂ Carbon Dioxide (laser)
CRO Cathode Ray Oscilloscope
c.w. Continuous Wave (laser)
d.c. Direct Current
DSR Display Safety Record
DVM Digital Voltmeter
EL Exposure Limit
ELBO Errant Laser Beam Occurrence
EMI Electro-Magnetic Interference
EN Europäische Norm (European Standard)
FDA Food and Drug Administration
FET Field Effect Transistor
GaP Gallium Phosphide (photodiode)
GaAsP Gallium Arsenide Phosphide (photodiode)
Ge Germanium (photodiode)
GUI Graphical User Interface
HgCdTe Mercury Cadmium Telluride (detector)
HSE Health and Safety Executive
IEC International Electrotechnical Commission
InGaAs Indium Gallium Arsenide (photodiode)
IR Infrared radiation (see Table A5.1 for spectral regions)
IRPA International Radiation Protection Association
ISO International Standards Organisation
LED Light Emitting Diode
LiTaO₃ Lithium tantalate (pyroelectric material)
LSB Least Significant Bit
MPE Maximum Permissible Exposure
MSB  Most Significant Bit
NAMAS  National Measurement Accreditation Service
NDF  Neutral Density Filter
Nd:YAG  Neodymium Yttrium Aluminium Garnet (laser)
NOHD  Nominal Ocular Hazard Distance
PC  Personal Computer
r.m.s  root mean square
SBN  Strontium barium niobate (pyroelectric material)
Si  Silicon (photodiode)
SiC  Silicon Carbide (photodiode)
SZL  Spectator Zone Limit
TGS  Triglycine sulphate (pyroelectric material)
TLV  Threshold Limit Value
UV  Ultraviolet radiation (see Table A5.1 for spectral regions)
VIS  Visible radiation (see Table A5.1 for spectral regions)

\[ \alpha \]  Angular subtense of a source at the eye of an observer
\[ \alpha_{\text{max}} \]  The value of \( \alpha \) above which MPEs are independent of source diameter
\[ \alpha_{\text{min}} \]  The value of \( \alpha \) above which a source is considered to be extended.
A  Absorption coefficient
a₁  Eye to source distance
a₂  Focal length of eye
C  Capacitance
C_D  Capacitance of a pyroelectric detector
C_F  Transimpedance amplifier feedback capacitance
C_j  Photodiode junction capacitance
C_L  Load capacitance
C_T  Thermal capacitance
C_6  Extended source MPE correction factor
d_r  Retinal image diameter
d_s  Source diameter
e  Emissivity
e  Electronic charge \( (1.602 \times 10^{-19} \text{ C}) \)
f  Frequency
\( \Delta f \)  Noise bandwidth
I  Current
I_{\text{bias}}  Operational amplifier bias current
I_d  Dark current (photodiode)
\( I_n \) r.m.s. noise current
\( I_p \) Photocurrent
\( I_s \) r.m.s shot noise current
\( I_t \) r.m.s thermal noise current
\( k \) Boltzmann's Constant \((1.381 \times 10^{-23} \text{ J/K})\)
\( K \) Constant
\( N \) Number of pulses
\( p \) Incident intensity
\( Q \) Radiant exposure
\( r \) Correlation coefficient
\( R \) Resistance
\( R_D \) Pyroelectric detector loss resistance
\( R_F \) Transimpedance amplifier feedback resistance
\( R_L \) Load resistance
\( R_0 \) Optical reflection at normal incidence
\( R_S \) Series resistance
\( R_{SH} \) Shunt resistance
\( R_T \) Thermal resistance
\( R_t \) Thermopile detector resistance
\( \sigma \) Population standard deviation
\( \tau \) Exposure duration
\( \tau_{\text{charge collection}} \) Charge collection time
\( \tau_{\text{diffusion}} \) Charge diffusion time
\( \tau_{\text{electrical}} \) Electrical (RC) time constant
\( \tau_{\text{response}} \) Detector rise time
\( T \) Absolute temperature
\( t \) Pulse width
\( V_n \) r.m.s Johnson noise voltage
\( V_{\text{offset}} \) Operational amplifier offset voltage
\( V_{\text{peak}} \) Maximum voltage
\( \omega_0 \) Natural resonant frequency of a tuned circuit
\( x \) Distance
<table>
<thead>
<tr>
<th>1. INTRODUCTION</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1. THE BACKGROUND TO LASER SAFETY</td>
<td>1</td>
</tr>
<tr>
<td>1.2. STRUCTURE OF THE THESIS</td>
<td>4</td>
</tr>
<tr>
<td>2. LITERATURE REVIEW</td>
<td>6</td>
</tr>
<tr>
<td>2.1. INTRODUCTION</td>
<td>6</td>
</tr>
<tr>
<td>2.2. ANALYSIS OF THE LASER SAFETY STANDARD</td>
<td>7</td>
</tr>
<tr>
<td>2.3. MEASUREMENT EQUIPMENT FOR HAZARD ASSESSMENT</td>
<td>33</td>
</tr>
<tr>
<td>2.4. DETECTORS</td>
<td>43</td>
</tr>
<tr>
<td>2.5. HUMAN FACTORS IN LASER RADIATION SAFETY</td>
<td>63</td>
</tr>
<tr>
<td>2.6. SUMMARY</td>
<td>68</td>
</tr>
<tr>
<td>3. INVESTIGATION OF THE MEASUREMENT TASK</td>
<td>70</td>
</tr>
<tr>
<td>3.1. INTRODUCTION</td>
<td>70</td>
</tr>
<tr>
<td>3.2. STUDY OF TYPICAL APPLICATIONS</td>
<td>71</td>
</tr>
<tr>
<td>3.3. INSTRUMENT SPECIFICATIONS</td>
<td>91</td>
</tr>
<tr>
<td>3.4. SUMMARY</td>
<td>94</td>
</tr>
<tr>
<td>4. DESIGN OF THE DETECTOR HEADS</td>
<td>95</td>
</tr>
<tr>
<td>4.1. INTRODUCTION</td>
<td>95</td>
</tr>
<tr>
<td>4.2. DESIGN OF THE PHOTodiode DETECTOR HEAD</td>
<td>97</td>
</tr>
<tr>
<td>4.3. DESIGN OF THE PYROELECTRIC DETECTOR HEAD</td>
<td>118</td>
</tr>
<tr>
<td>4.4. DESIGN OF THE THERMOPILE DETECTOR HEAD</td>
<td>128</td>
</tr>
<tr>
<td>4.5. OPTICAL DESIGN</td>
<td>138</td>
</tr>
<tr>
<td>4.6. SUMMARY</td>
<td>143</td>
</tr>
<tr>
<td>5. DESIGN OF THE INSTRUMENT</td>
<td>145</td>
</tr>
<tr>
<td>5.1. INTRODUCTION</td>
<td>145</td>
</tr>
<tr>
<td>5.2. DESIGN OF THE INTERFACE UNIT</td>
<td>146</td>
</tr>
<tr>
<td>5.3. DESIGN OF THE COMPUTER SOFTWARE</td>
<td>157</td>
</tr>
<tr>
<td>5.4. COMMERCIAL DEVELOPMENT OF THE MPE METER</td>
<td>167</td>
</tr>
<tr>
<td>5.5. SUMMARY</td>
<td>169</td>
</tr>
<tr>
<td>6. RESULTS AND ACCURACY CONSIDERATIONS</td>
<td>170</td>
</tr>
<tr>
<td>6.1. INTRODUCTION</td>
<td>170</td>
</tr>
<tr>
<td>6.2. TESTING OF THE DETECTOR HEADS</td>
<td>171</td>
</tr>
<tr>
<td>6.3. TESTS OF THE INTERFACE UNIT</td>
<td>181</td>
</tr>
<tr>
<td>6.4. DETERMINATION OF THE INSTRUMENT PRECISION</td>
<td>183</td>
</tr>
<tr>
<td>6.5. CALIBRATION TECHNIQUES</td>
<td>198</td>
</tr>
<tr>
<td>6.6. SUMMARY</td>
<td>206</td>
</tr>
<tr>
<td>7. EXTENSION OF THE INSTRUMENT FUNCTIONALITY</td>
<td>208</td>
</tr>
</tbody>
</table>
7.1. INTRODUCTION 208
7.2. HIGH POWER LASER BEAM MEASUREMENT 210
7.3. SUMMARY 222

8. CONCLUSIONS 223

9. FURTHER WORK 228
9.1. INSTRUMENT DEVELOPMENT 228
9.2. ALTERNATIVE MEASUREMENT APPLICATIONS 230

10. REFERENCES 231

11. APPENDICES 240
11.1. APPENDIX 1: LINEAR DRIVE BOARD FOR LEDS 240
11.2. APPENDIX 2: PULSE DRIVE BOARD FOR LEDS 242
11.3. APPENDIX 3: PULSE GENERATION USING AN ARGON-ION LASER 243
11.4. APPENDIX 4: METHOD OF DETERMINING DETECTOR SPATIAL NON-UNIFORMITY 244
11.5. APPENDIX 5: LASER RADIATION INJURY 245
11.6. APPENDIX 6: LASER SAFETY STANDARDS 249
11.7. APPENDIX 7: WAVELENGTH MEASUREMENT TECHNIQUES 257
11.8. PUBLICATIONS ARISING FROM THE RESEARCH 264

12. GLOSSARY 266
INTRODUCTION

1.1 THE BACKGROUND TO LASER SAFETY

Interest in the safety of lasers dates from 1962 [1]. At this time laser technology was recently developed and the most significant users were military organisations. The military drove the early development of safety standards and concentrated on radiation hazards alone [1]. As the variety of lasers increased and civilian applications were found, other hazards became apparent.

The hazards associated with lasers may be divided into four groups; optical radiation hazards, chemical hazards, electrical hazards and miscellaneous hazards. Optical radiation hazards are not restricted to the laser energy. Hazardous radiation may also be generated as part of the laser application, for example ultraviolet light emission from the laser-target interaction during material processing [2]. Hazards other than the laser radiation are termed "associated hazards" [3]. Similar hazards exist in the general industrial environment, hence control strategies exist. The levels of laser radiation which may be hazardous, and strategies for controlling the hazards are addressed by an internationally recognised Standard [3].

In a given laser application the significance of individual hazards is modified by factors including the laser type, the operating environment and the personnel with access to the laser. To ensure safe laser operation it is necessary to adopt measures to control the appropriate hazards. Hazard control measures may be divided into three groups; engineering controls, administrative controls and the use of personal protective equipment [3]. Figure 1.1 summarises the process of ensuring laser safety.

Engineering controls are not explicitly defined in the current laser safety standard [3] although examples of engineering controls are described. Engineering controls may be regarded as physical functions designed into the laser system to control specific hazards. An example is an enclosure to prevent access to hazardous radiation.

Administrative controls are defined as "Safety measures of a non-engineering type such as; key supervision, safety training of personnel, warning notices, count down procedures and range safety controls" [3]. Engineering controls can directly remove
hazards whereas administrative controls can only help to avoid the creation of situations in which hazards are present.

Personal protective equipment includes items such as eyewear and clothing intended to protect against hazards. The standard [3] emphasises that the need for personal protective equipment should be minimised by the use of engineering design and administrative controls. It is appropriate to regard hazard control measures as being in a hierarchy. Engineering controls always take the greatest precedence, followed by administrative controls where necessary. Personal Protective Equipment is only used where hazards are anticipated to remain despite the application or consideration of all other control measures.

In a given laser application it is necessary to verify that the hazard control measures adopted are sufficient to make the laser operation safe. The first stage to this process is to check for the presence or absence of hazard control features as described in the
Standard [3]. This is a simple rule based exercise in which a list of requirements and recommendations is checked against those implemented in the laser system. The second stage requires verification that the controls which have been implemented are effective in operation and that no hazards remain. This final stage may require measurement of the radiation hazards.

Laser safety standards concentrate on radiation hazards. It was found that two significant problems relating to laser radiation hazard assessments existed. Firstly the existing commercially available instrumentation was badly matched to the specific technical requirements of laser radiation hazard assessments. Secondly the end users of the standard who performed hazard assessments found that the standards were excessively complex to interpret and use. These limitations are shown to have resulted in situations where genuine radiation hazards have not been identified. Development of instrumentation for laser safety was therefore aimed primarily at resolving the technical and user interface aspects of laser radiation measurement issues for hazard assessments.

Examination of the measurement requirements revealed that energy measurement is critical to hazard analysis and defines many of the measurement requirements. A novel method for accurately measuring the energy of short optical pulses using photodiodes was developed as part of the instrument strategy. Analogue signal processing solutions were designed to overcome specific performance limitations of the other detector types required as part of the instrument strategy.
1.2 STRUCTURE OF THE THESIS

In Chapter 2 fundamental aspects of laser radiation safety are considered. The laser safety standard is analysed in detail. This defines many of the technical requirements for laser radiation hazard assessments. The role of measurements as part of the task of laser radiation safety is considered. The currently available instrumentation for performing laser radiation hazard assessments is examined. There are two groups of instruments, commercially available general purpose laser radiation measurement equipment and task specific instrumentation produced by other researchers. Both groups are examined. Detectors for laser radiation measurement are examined in detail in order to determine suitable types for the instrument. Finally the human factors in laser safety are examined. This involves a review of the suitability of the laser safety standards for the users and aspects of instrument user interfacing.

Laser radiation hazard assessments were performed on two typical laser applications. Instruments were selected to be representative of the types which were known to be used. Where necessary these instruments were supplemented with purpose built equipment. Chapter 3 contains accounts of this work and discusses the limitations which became apparent in the equipment for laser radiation hazard assessment. A set of instrument specifications are developed on the basis of the work in Chapters 2 and 3.

The description of the instrument design begins in Chapter 4 with the design of the detector heads. Three detector types were selected as being suitable for the instrument; photodiodes, pyroelectric detectors and thin film thermopile detectors. The theoretical performance of the detectors described in Chapter 2 is supplemented by practical tests to determine suitable devices. Designs for each detector type are presented. The designs compensate for specific detector limitations and provide signal outputs appropriate for the requirements of laser radiation hazard assessment. Optical aspects of the detector head design are considered.

Chapter 5 continues the instrument design with the interface unit and the computer software used to perform the hazard calculations.
The performance of the prototype instrument was evaluated, with particular attention to the measurement precision. The results of this work are presented in Chapter 6. Sources of the dominant precision and systematic errors are described. The discussion then leads into calibration techniques appropriate to the instrument.

In Chapter 7 the application of the instrument beyond laser radiation hazard assessments is considered. A technique for high power laser measurement is demonstrated and found to have additional safety related functions.

Conclusions from the work are presented in Chapter 8. Areas for further work related to the instrument development and other applications developed during the research are contained in Chapter 9. A description of the commercially available instrument which has been developed from the prototype instrument is provided in Chapter 9. Chapter 10 contains the references cited in the thesis. Appendices contain additional information on the test methods used for the prototype instrument, a discussion of the theory behind biological laser radiation damage, an account of the development and current status of laser safety standards, a brief account of an initial investigation into low cost methods of laser wavelength measurement and a list of the publications arising from the research.
2 LITERATURE REVIEW

2.1 INTRODUCTION

The international laser safety standard [3] is used as a basis for defining many of the measurement requirements. Concepts of safe exposure levels and of laser classification are used by the standard and the practical implications of these on MPE assessments are discussed in this Chapter. A detailed analysis of the standard and other supporting literature is used to define many of the measurement requirements for laser radiation hazard assessments.

In order that the instrument may be matched to the task of laser radiation hazard assessment it is important to consider the human factors involved in the assessment process. Two aspects are considered; the suitability of the information provided by the standard and the requirements for the user interface on the instrument. The requirements for the user interface form a second stage to the development of instrument specifications when combined with the analysis of the measurement requirements of the standard.

Having defined the important performance and user interface aspects of instrumentation for laser radiation hazard analysis it is possible to examine the measurement process in greater detail. Firstly the role of measurements in laser radiation safety is examined. The content of relevant instrumentation standards is then reviewed. Two approaches to making measurements for laser radiation hazard assessment are considered;

1. using standard laser power and energy meters, or

2. using dedicated instrumentation.

Commercially available, general purpose laser power and energy measurement equipment was examined and found to have several limitations. Some previous work has been reported on the design of instrumentation specifically for laser radiation hazard assessment. The operation and limitations of this equipment is reviewed.
The range of available detector types which could be used in a laser radiation measurement system are considered. From the range of available detectors, three types are selected and relevant aspects of the detector performance examined in greater detail.

2.2 ANALYSIS OF THE LASER SAFETY STANDARD

2.2.1 Introduction

The historical development and current status of laser safety standards are described in Appendix 6. Throughout this thesis the current British Standard BS EN 60825-1 1994 [3] will be used unless otherwise stated. This standard is harmonised throughout Europe and is identical to IEC 825-1 which is applicable internationally (with the exception of North America). Application specific standards exist for optical fibre communication systems [4] and display lasers [5,6]. These utilise the exposure limits provided in BS EN 60825-1 1994 and are described in Appendix 6.

BS EN 60825-1 is the fundamental source of laser radiation safety information. Safe exposure levels are defined as functions of wavelength and exposure duration. Analysis of these safe exposure levels is essential in defining the task of laser radiation hazard assessment.

2.2.2 Exposure levels and classification

It is necessary to have a defined safe exposure level to laser radiation before it is possible to determine the control measures required to avoid exposure to hazardous levels of radiation. Exposure limits have been determined by extrapolation from experimentally determined damage thresholds at specific wavelengths and exposure durations [7]. In the majority of cases a threshold for acute injury exists. It is then possible to define hazardous levels of radiation, intermediate levels of radiation where the hazard depends on individual susceptibilities and safe levels. Acute damage thresholds for ultraviolet radiation may be determined, but definition of chronic damage thresholds is not feasible. In this situation the natural exposure level to ambient ultraviolet radiation was used to set an exposure limit [7].
Various agencies have used experimental laser damage threshold information to define safe exposure limits. These limits are termed exposure limits (ELs) [8], Threshold Limit Values (TLVs) [9], or Maximum Permissible Exposures (MPEs) [3]. For consistency the term Maximum Permissible Exposure will be used when referring to safe exposure limits. MPE values are set below known hazard levels and are based on the data from experimental studies [3]. It is not possible to absolutely exclude the possibility of adverse reactions by some individuals to exposure at the MPE. Consequently the MPE value should be regarded as an absolute maximum for exposure and not a working limit. Exposure should be minimised as far as reasonably practical.

A system of classification for laser hazards is given in the standard [3]. Such classification systems are common where in other situations where hazards from a process exist. Classification is on the basis of the control measures required in each group. It is not based only on the level of risk of a hazardous exposure occurring [10]. Such an approach would lead to many different classification groups based on laser power which would be contrary to the need for a simple classification system. Control measures to preclude a hazardous exposure are common to a much wider range of laser powers and are therefore a more suitable basis for classification. The lowest classification number is associated with the laser least likely to cause injury. Changeover between classes is based on power or energy levels derived from MPE values. Table 2.1 summarises the classes, the relation to the MPE and the relative degree of hazard control required. The standard [3] provides detailed information on the hazard control measures required in each class.

Class 1 lasers or laser products do not permit access to radiation exceeding the MPE for a given exposure duration. Examples are laser printers and CD players and fixed barcode scanners used in supermarket checkouts. Class 2 and 3A lasers rely on the aversion response of the eye to bright light to limit exposure duration and ensure that the MPE is not exceeded. For Class 3A lasers viewing of laser beam is only below the MPE if optical aids such as binoculars are not used. These could collect more radiation and concentrate it into the eye. Minimal control measures are required for lasers in these classes. Hand held bar code scanners are usually Class 2 devices. The
Class 3A subdivision was introduced following pressure from the construction industry to relax the hazard control measures required with many laser devices used for alignment [1]. Class 3B lasers emit radiation which may be hazardous unless viewed as a diffuse reflection. This represents a breakpoint, above which significant control methods are required to prevent hazardous exposure. Finally Class 4 lasers are hazardous under any viewing conditions and may also cause skin burns and present fire risks. The most advanced hazard control measures are therefore required.

<table>
<thead>
<tr>
<th>Class</th>
<th>Relationship to MPE</th>
<th>Degree of radiation hazard control required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 1</td>
<td>MPE cannot be exceeded.</td>
<td>None</td>
</tr>
<tr>
<td>Class 2</td>
<td>Exposure limited by the blink reflex; MPE not exceeded unless this is overcome.</td>
<td>Minimal</td>
</tr>
<tr>
<td>Class 3A</td>
<td>Exposure limited by the blink reflex; MPE not exceeded unless this is overcome.</td>
<td>Some</td>
</tr>
<tr>
<td></td>
<td>Optical aids may cause MPE to be exceeded.</td>
<td></td>
</tr>
<tr>
<td>Class 3B</td>
<td>MPE exceeded by beam, not be a diffuse reflection.</td>
<td>Significant</td>
</tr>
<tr>
<td>Class 4</td>
<td>MPE exceeded.</td>
<td>Many</td>
</tr>
</tbody>
</table>

Table 2.1 : Summary of the classification used by BS EN 60825-1

The classification system exists for manufacturers (defined to include anyone who by modifying a laser, or installing it in an enclosure changes the classification [3]). Laser users can then apply appropriate hazard control measures on the basis of the information supplied by the manufacturer. Maximum Permissible Exposure values are provided for the user to determine whether a hazard exists in their system. This can be extended to include verifying that hazard control measures applied to a given class of laser are effective in preventing potentially hazardous exposures. Safety inspectors have an interest in MPEs when verifying that an installation which is claimed to be safe presents no hazard.

Determination of exposure duration is important in the determination of MPE values and therefore in classification. It is unusual for exposure duration to be defined by the operating duration of the laser. Alternative physiological and behavioural factors are
used to predict probable maximum exposure durations. These are now widely accepted [7,10,11].

Exposure to bright sources of visible light causes an aversion response, commonly termed the blink reflex. This causes the eye to be closed and is assumed to operate within a worst case of 0.25s [1]. At longer wavelengths no visual stimulation occurs and alternative factors limit exposure. In the near infra red over wavelengths for which the eye focuses radiation (700nm to 1400nm) unintentional eye movements (saccades) distribute the focused laser beam over an extended area. Since the beam is invisible there is no reason for an individual to fixate on it and overcome the saccades.

Wavelengths longer than 1400nm generate a thermal response over periods of several seconds resulting in an automatic aversion. A 10s limiting exposure duration is regarded as appropriate given these controlling factors. The 10s exposure duration for infrared radiation is recommended by ANSI [12], IRPA [13] and ACGIH [14]. BS EN 60825 (1991) recommended the use of a 1000s exposure duration for classification. This was relaxed in the latest version [3] to 100s which was stated at the time to be a conservative recommendation [10]. A contradiction to the use of a 100s limiting exposure duration exists in the latest standard; Example A4.2 in the latest standard [3] concerns the MPE assessment of a 1.06μm laser, and recommends that a 10s exposure duration be applied.

Wavelengths shorter than 400nm (ultraviolet) are regarded differently because the effects of exposure to ultraviolet radiation are additive. Accordingly the limiting exposure duration is taken to be that of a working day (30 000s). All of the limiting exposure durations must be applied with care; reflexes can be overcome and there has been recent concern that the limited apparent brightness of some lasers (for example 670nm laser diodes) delays the blink reflex [15].

Laser radiation hazard assessment is a three stage process; firstly the laser radiation level must be correctly measured or calculated, secondly the MPE must be determined, finally the values must be compared. Measurement of the radiation level requires a measurement aperture to be physically defined. The aperture relates to the interaction between laser radiation and irradiated tissue. A 7mm diameter aperture is used for
visible and near infrared exposures, this represents a maximally dilated pupil [1]. A 1mm diameter aperture is used for ultraviolet exposures. Apertures of 1mm or 3.5mm diameter are used for infrared exposures shorter than 100μm. The smaller diameter apertures are used to ensure that any "hotspots" in the incident radiation are not averaged out by the measurement process [1]. The 3.5mm diameter is used for infrared exposures lasting longer than 3s where hotspots are averaged out by thermal conduction in irradiated tissue [16]. For infrared exposures to wavelengths longer than 100μm an 11mm diameter aperture is required. The larger aperture is necessary to avoid measurement errors associated with diffraction effects [1]. The MPE is calculated by selecting the appropriate expression from a standard and inserting into it values for exposure duration and wavelength as necessary. Conceptually the MPE assessment process is straightforward, in practice there are practical difficulties.

2.2.3 Assessment of c.w. sources

MPE values given in the standard are in terms of irradiance (Wm⁻²) or radiant exposure (Jm⁻²). The area term relates to the measurement aperture rather than the cross section of the laser beam. Fitting the appropriate aperture to a detector reduces the task to a power. A single measurement of instantaneous power will only accurately predict the radiation hazard if the laser output is constant. It is preferable to take a series of readings to ensure that any fluctuations in beam power are recorded and that the maximum power is measured. A more exhaustive approach requires that the maximum irradiance and total radiant exposure over a period are measured. Measured maximum and derived average irradiance can be compared; any significant differences warn of a complex laser output characteristic requiring detailed investigation. Limited biological hazard data means that very little guidance is provided in the standard [3] on the assessment of such sources.

It is not necessarily practical to measure the true total radiant exposure over the exposure duration. As an example a supermarket checkout operator could be considered to have an exposure duration of a full working day (regarded as being equivalent to 30 000s for classification). An assessment where each measurement has 30 000s duration and several measurements are required to determine the worst case is
impractical. Realistic measurement periods are in the range one to ten seconds. Basic sampling constraints mean that changes having a period longer than the measurement duration would not be accurately resolved. A measurement period shorter than one second may not therefore sufficiently characterise a laser source. Measurement periods exceeding ten seconds will provide a more accurate value of radiant exposure if laser power is fluctuating slowly, but only if the detector alignment can be kept constant. It may not always be practical for the detector to be rigidly mounted in the measurement position. In such cases it would be necessary for the operator to hold the detector. Training of the operator to good radiometric practice is important to reduce the errors which could be introduced by a hand held detector. Such errors will be exacerbated by a long measurement period, uncertainties in detector position over periods longer than ten seconds would become significant. Total radiant exposure over the exposure duration may be determined by extrapolation from the measured value. The approximation to true radiant exposure can be improved by making multiple measurements. This reduces the probability of short duration peaks of irradiance being missed.

2.2.4 Assessment of pulsed sources

Measurements of pulsed laser radiation for MPE assessments are more complex than c.w. lasers. Detector requirements are more exacting, and the calculation of MPE thresholds is more complex. The detector requirements are more demanding because the pulse irradiance increases as the pulse width decreases, but the irradiance averaged over a fixed exposure duration decreases (assuming the pulse repetition rate remains constant). For example the MPE of a single 100µs pulse of visible laser radiation is $18 \times 10^3$ Jm$^{-2}$, this corresponds to a pulse irradiance of 180Wm$^{-2}$ but an average irradiance of only $18 \times 10^3$ Wm$^{-2}$. Equipment must therefore be capable of simultaneously measuring short pulses of high peak irradiance whilst being immune to a constant background level from both ambient radiation and electronic noise.

When assessing a pulsed laser source the standard [3] presents three requirements. The most restrictive condition must be applied.
1. "The exposure from any single pulse within a pulse train shall not exceed the MPE for a single pulse."

2. "The average exposure for a pulse train of duration \( T \) shall not exceed the MPE for a single pulse of duration \( T \)."

3. "The exposure from any single pulse within a pulse train shall not exceed the MPE for a single pulse multiplied by the \( N^{0.25} \) where \( N \) is the number of pulses expected in an exposure. In some cases this value may fall below the MPE that would apply for continuous exposure at the same peak power using the same exposure time. Under these circumstances the MPE for continuous exposure may be used."

The third condition is only applied for lasers operating at wavelengths longer than 400nm and pulses shorter than 0.25s.

The first two conditions ensure that individual pulses do not contain sufficient energy to cause damage and that the total energy received during an exposure is not sufficient to cause damage. The third condition relates to damage caused by the cumulative effect of a pulse train and is termed the reduced single pulse MPE. At wavelengths shorter than 400nm this third condition is not applied because the damage mechanism becomes photochemical rather than thermal and exposures are considered to be additive over an exposure duration [7,11].

Many of the MPE expressions are based on research into biological damage thresholds which demonstrated that "The total energy (damage) threshold for a train of pulses increases as the total on time (exposure) raised to the power of \( \frac{3}{4} \)" [1]. The expression for the MPE contained in the standard for wavelengths between 400nm and 1.4\( \mu \)m and a wide range of exposure durations is based on this finding:

\[
\text{MPE} = K \times \tau^{0.75} \text{Jm}^{-2}
\]

where \( K = 18 \) for \( 400 < \lambda < 1050 \text{ nm} \), \( \tau = \text{exposure duration (single pulse)} \)

The reduced single pulse MPE also originates from this finding. Assuming that energy is delivered as a pulse train with equal pulse width:
Total energy = \( N \times Q \)

where \( Q = \) radiant exposure per pulse, \( N = \) number of pulses in exposure duration

Total on time = \( N \times t \)

where \( t = \) pulse width

If the total energy of a train of \( N \) pulses must not exceed the MPE for the total on time:

\[ N \times Q < K \times [N \times t]^{0.75} \]

re-arranging:

\[ Q < N^{-0.25} \times K \times t^{0.75} \]

Which is the expression specified by the standard for the calculation of reduced single pulse MPE. Beyond 1.4\( \mu \)m the MPE expression becomes proportional to \( t^{0.25} \). Given that the temporal dependency for a single pulse has changed it would be reasonable to expect the correction factor for a train of pulses to differ. Applying the same reasoning as for shorter wavelengths a correction factor of \( N^{0.75} \) would be appropriate.

In the ANSI standard [12] the reduced single pulse condition is only applied between 400nm and 1.4\( \mu \)m [17]. The application of the reduced single pulse MPE for all wavelengths longer than 400nm may be an error in the standard. Schumeister [18] claims that the existing assessment does not accurately predict the hazard of pulse trains of any wavelength and proposes an alternative set of MPE expressions.

The dependency of the MPE for a pulse train on total on time and total energy is significant because it implies that the mode of energy delivery is irrelevant. The reduced single pulse criterion is merely a convenient interpretation for repetitive, consistent pulse trains. The radiation hazard of a pulse train may determined by measurement of the total radiant exposure. It is still essential to verify that no deviant pulse exists which would exceed the single pulse MPE. Unless every pulse in the train was identical in duration and energy measurement of individual pulses would be necessary to verify that none exceeded a single pulse MPE. Figure 2.1 summarises the two extreme variations in pulse parameters which can be envisaged:
1. The pulse width remains unaltered, but some pulses have a higher peak power and therefore increased energy;

2. The pulse power remains constant whilst the pulse width increases causing an increase in pulse energy.

\[ \text{Standard pulse train} \]

\[ \text{Pulse train with deviant high power pulse (case 1)} \]

\[ \text{Pulse train with deviant long pulse (case 2)} \]

Figure 2.1 : Examples of pulse trains containing deviant pulses

In each case the potential hazard arises because the deviant pulse could exceed the single pulse MPE for the specific parameters associated with the pulse. The effect on the overall hazard of the pulse train would depend on the frequency of the deviant pulses. In many cases a single deviant pulse would make negligible difference to the hazard of a pulse train. Measurement of total on time and total radiant exposure would permit the hazard of a pulse train to be determined, regardless of any deviant pulses.

Considering the MPE expressions for two pulses:

\[ \text{MPE}_1 = K \times N^{-0.25} \times t_1^{0.75} \]

For the train of \( N \) pulses of duration \( t_1 \) and;

\[ \text{MPE}_2 = K \times t_2^{0.75} \]

For a single deviant pulse with duration \( t_2 \).

The hazard exists if a deviant pulse exceeds \( \text{MPE}_2 \) when it is assumed that each pulse is at or below \( \text{MPE}_1 \). Taking the ratio of \( \text{MPE}_2 \) to \( \text{MPE}_1 \) gives a measure of how much
increase in single pulse energy would be permissible before the deviant pulse presented a hazard.

Relative MPE = \frac{K x t_2^{0.75}}{K x N^{-0.25} x t_1^{0.75}} = \left(\frac{t_2}{t_1}\right)^{0.75} x N^{0.25}

Considering case 1, an increase in pulse power at constant pulse width can be detected by measuring the maximum detector output. The measured maximum value would be compared to the average value of the train to determine whether a deviant pulse was present. The N^{0.25} factor introduces an increasing difference between the single pulse MPE and the reduced single pulse MPE. The greater the number of pulses in the measurement duration, the greater the maximum power of a deviant pulse would have to be to exceed the single pulse MPE. For example sixteen pulses during an exposure duration makes the reduced single pulse MPE half of the single pulse MPE. A deviant pulse would have to have twice the energy of other pulses in the train to exceed the single pulse MPE. It becomes increasingly unlikely that individual pulses will deviate sufficiently from the average to exceed the single pulse MPE as the repetition rate increases. A deviant pulse which exceeded the single pulse MPE would have a maximum power significantly above the remainder of the pulses in the train and could easily be detected.

Case 2 presents a more complex scenario, the pulse power is constant, but the pulse width varies. The single pulse MPE is a function of the width of a specific pulse. It would be necessary to measure the duration of each pulse to check that none deviated from the average. This is not as straightforward as measuring the maximum detector output. Closer investigation of the change in pulse width required to exceed the single pulse energy MPE shows that it is unlikely that such a deviant pulse in a pulse train would exist.

The relative change in pulse energy arising from the change in pulse width is given by:

\frac{t_2}{t_1}

The relative hazard can be determined from the ratio of the change in pulse energy to the change in relative MPE.
Relative Hazard = \frac{t_2^{0.75} \times t_1^{0.25}}{t_2^{0.75} \times t_1^{0.25}} \times \frac{1}{N^{0.25}} = \left(\frac{t_2}{t_1}\right)^{0.25} \times N^{-0.25}

Assuming that the total on time of the pulse train is much greater than the duration of any individual pulse (N large) then the pulse of duration $t_2$ will have negligible effect on the total exposure duration. By inspection, if the relative hazard is not to increase above unity (implying that if the measured radiation was equal to the reduced single pulse MPE, a deviant pulse would exceed the single pulse MPE) the relative increase in pulse width ($t_2/t_1$) must be less than or equal to N.

As N increases it becomes increasingly unlikely that a deviant pulse of sufficient duration to exceed a single pulse MPE will exist. Measurement of the total radiant exposure, total exposure duration and number of pulses to determine the reduced single pulse MPE is therefore adequate to exclude the possibility of a deviant long pulse exceeding the MPE. Measurement of maximum pulse power is straightforward and sufficient to detect deviant pulses with greater than average pulse power.

The user should not be relied upon to judge whether the radiation to be measured is c.w. or pulsed. Persistence of human vision causes pulses with a repetition rate greater than 40-50Hz to appear as continuous illumination (for lasers emitting visible wavelengths). If a measurement was made using an average reading c.w. meter then the failure to measure the higher peak power of individual pulses could cause the hazard to be underestimated.

The period used for the measurement is subject to the same conflicting requirements as c.w. lasers. Sampling problems introduced by short measurement durations are especially significant for low repetition rate pulse trains. The assessment of the hazard will vary according to the number of pulses within the measurement "window". Assessments where the exposure duration is long in comparison to the measurement period will be particularly affected because of the extrapolation used to predict the number of pulses in the exposure duration. A one second measurement period provides a satisfactory balance between the opposing constraints. For lasers emitting pulses at repetition rates below 10Hz variations from measurement to measurement in the total radiant exposure and number of pulses will occur. The effect of this may be
reduced by averaging a number of measurements. Alternatively it would be possible to consider synchronising the start of a measurement to a pulse edge.

2.2.5 *Pulse width and repetition rate resolution requirements*

An additional aspect of pulsed laser radiation hazard assessment is determining the pulse widths which must be resolved. The MPE expressions in the standard [3] include sub-nanosecond pulses. To resolve all possible pulse widths would therefore require wide bandwidth electronic circuitry. The bandwidth would have to be obtained with minimal excess noise generation to avoid errors with low level signals. Hardware with such features would be expensive.

An examination of the MPE expressions enables more realistic specifications for pulse resolution to be determined in many spectral regions. The first control of the minimum pulse width to be resolved and measured is the pulse width at which the single pulse MPE changes from being time dependent to being a constant radiant exposure. Once the single pulse MPE becomes a constant radiant exposure (independent of pulse width) there is no need to measure pulse width in order to determine the hazard. It is only necessary to measure the pulse radiant exposure to verify that the single pulse MPE is not exceeded.

The second control of minimum pulse width to be resolved originates from the reduced single pulse MPE. For pulsed lasers operating at wavelengths longer than 400nm the most restrictive of the single pulse MPE, the reduced single pulse MPE and the average exposure MPE should be applied. A clause is included in the standard to prevent the reduced single pulse MPE from becoming inappropriately restrictive. This is based on the common sense observation that if the pulse power corresponding to the reduced single pulse MPE falls below that corresponding to continuous exposure at the same power over the same exposure duration, then the MPE for continuous exposure should be applied. It would make no biological sense if a pulse train was regarded as hazardous, yet had lower power and lower energy than a continuous exposure.
At low repetition rates the reduced single pulse MPE applies, this will always be more restrictive than the single pulse MPE (excluding the case of one pulse). As the pulse repetition rate increases, the reduced single pulse MPE decreases, until ultimately the continuous exposure MPE or average power MPE will apply. For constant pulse width, an increase in repetition rate will increase the average power of the pulse train. The average power MPE may therefore become the limiting value before the continuous exposure MPE. Expressions for the maximum number of pulses for which the reduced single pulse is the limiting MPE may be derived for the spectral subdivisions in the MPE table. Once the continuous exposure or average power MPE apply it is no longer necessary to resolve the individual pulses, only to measure the total radiant exposure over the exposure duration. A means of detecting deviant pulses is still required.

Table 2.2 contains the pulse widths below which the MPE becomes independent of pulse width for each spectral subdivision of the standard.

<table>
<thead>
<tr>
<th>Wavelength region (nm)</th>
<th>Minimum pulse width to be resolved</th>
</tr>
</thead>
<tbody>
<tr>
<td>180 to 302.5</td>
<td>MPE dependent on total radiant exposure only.</td>
</tr>
<tr>
<td>302.5 to 315</td>
<td>1ns</td>
</tr>
<tr>
<td>315 to 400</td>
<td>1ns</td>
</tr>
<tr>
<td>400 to 550</td>
<td>18μs</td>
</tr>
<tr>
<td>550 to 700</td>
<td>18μs</td>
</tr>
<tr>
<td>700 to 1050</td>
<td>18μs</td>
</tr>
<tr>
<td>1050 to 1400</td>
<td>50μs</td>
</tr>
<tr>
<td>1400 to 1500</td>
<td>1ms</td>
</tr>
<tr>
<td>1500 to 1800</td>
<td>MPE dependent on total radiant exposure only.</td>
</tr>
<tr>
<td>1800 to 2600</td>
<td>1ms</td>
</tr>
<tr>
<td>2600 to 10⁶</td>
<td>100ns</td>
</tr>
</tbody>
</table>

Table 2.2: Minimum pulse widths to be measured for MPE assessment in each spectral region.

The majority of spectral regions can be addressed using a detector which is capable of resolving pulses with width greater than 18μs (and by implication, repetition rates below 56kHz). For pulses with a shorter width it is only necessary to measure the pulse energy, or if the repetition rate is greater than 56kHz, to measure the total...
energy over the measurement period. The detection of deviant pulses should be sensitive to maximum pulse irradiance for pulse widths greater than 18μs and maximum pulse radiant exposure for shorter pulses.

Potential measurement problems exist in the spectral region 302.5nm to 400nm and at wavelengths longer than 2600nm where short pulse widths have to be resolved to determine the MPE. Short minimum pulse duration implies a high maximum pulse repetition rate; 1GHz between 302.5nm and 400nm. Examination of the MPE expressions reveals that in practice the maximum pulse repetition rates before average exposure conditions apply are limited.

In the spectral region 302.5nm to 400nm it will be assumed that the exposure duration is greater than ten seconds. This includes the majority of probable exposure conditions, but excludes unusual cases such as the entire exposure being concentrated in a short burst of pulses. The reduced single pulse MPE is not applied, the most restrictive of the average exposure or single pulse conditions apply. At low repetition rates the single pulse condition is more restrictive than the average exposure because the total energy per second is low, even for large pulse energies. As the repetition rate increases it becomes more likely that the average exposure condition will be the limiting factor.

The MPE for pulses of width between 1ns and 10s is given by:

\[
\text{MPE} = 5600 \times t_p^{0.25}
\]

Where \(t_p\) is the pulse width.

The MPE for an exposure duration greater than ten seconds is typically 10 000Jm\(^2\). At the repetition rate of changeover:

\[
5600 \times t_p^{0.25} \times N = 10000
\]

Where \(N\) is the number of pulses over the exposure duration.

\(N\) is maximised at the minimum value of \(t_p\) (1ns). Substituting values gives:

\[
N = 318
\]
Which is equivalent to 31.8Hz repetition rate for an exposure duration of ten seconds (corresponding to maximum repetition rate) before the average exposure condition dominates the MPE assessment and pulse width becomes irrelevant.

For wavelengths longer than 2.6\(\mu\)m an exposure duration greater than or equal to ten seconds will be assumed. As with the ultraviolet spectral region this covers the majority of common exposure conditions. At wavelengths longer than 1.4\(\mu\)m a full comparison of average and single pulse MPEs would have to make allowance for the differing measurement apertures required by the standard [3]. For durations shorter than or equal to three seconds a 1mm diameter aperture is used, for durations longer than three seconds a 3.5mm diameter aperture is used. The biological basis for these is discussed in Marshall et al. [19] and the rationale behind IEC825-1 [16]. The practical implication is that the single pulse MPE condition will usually be measured using a 1mm diameter aperture whereas the average MPE will usually be measured using a 3.5mm diameter aperture. For the purposes of demonstrating the low changeover frequency between reduced single pulse and average MPEs the effect of neglecting the effect of apertures on the measured power and energy is negligible.

The contradiction between ANSI and IEC standards relating to the application of reduced single pulse exposure conditions beyond 1.4\(\mu\)m is significant (Section 2.2.4). If the reduced single pulse MPE limit is used then the individual pulse radiant exposure becomes lower. As a consequence a higher pulse repetition rate applies before the application of average exposure limits. Since this represents the worst case it will be used.

For an exposure duration greater than ten seconds the MPE is defined by a constant irradiance:

\[
\text{MPE}_{\text{AVERAGE}} = 1000 \text{Wm}^{-2}
\]

The reduced single pulse MPE is defined as a pulse radiant exposure:

\[
\text{MPE}_{\text{REDUCED \ SINGLE \ PULSE}} = 5600 \times t_p^{0.25} \times N^{-0.25} \text{Jm}^{-2}
\]

Where \(t_p\) is the pulse width and \(N\) the number of pulses over the exposure duration.
Over an exposure duration of \( \tau \) seconds the changeover between MPE limits occurs when the total energy of a train of pulses equals the energy permissible over the exposure duration:

\[
1000 = \frac{(5600 \times t_p^{0.25} \times N^{-0.25}) \times N}{\tau}
\]

Which rearranges to give:

\[
N = \left[ \frac{\tau}{5.6 \times t_p^{0.25}} \right]^{4/3}
\]

This expression gives the total number of pulses during the exposure duration. Pulse repetition rate is proportional to \( \tau^{1/3} \), consequently \( N \) is maximised for maximum \( \tau \) and minimum \( t_p \). An exposure duration of 30 000s and pulse width of 100ns give a maximum pulse repetition rate of 674Hz.

For most spectral regions a measurement strategy which is capable of measuring the energy of pulses shorter than 18\( \mu \)s without temporal resolution is appropriate. At repetition rates greater than 56kHz it is not necessary to resolve individual pulses, regardless of the pulse width. The maximum power of a pulse train of pulses longer than 18\( \mu \)s should be recorded, for shorter pulses the maximum pulse energy is important. The detailed examination of the two spectral regions where the MPE is dependent on short pulse widths shows that it is not necessary to resolve individual pulses above relatively low repetition rates. It is only necessary for the user to enter the pulse width for pulse trains of low repetition rates and for the pulse energy to be measured. These findings are important in determining the specifications for the instrument.

### 2.2.6 Power and energy ranges

An indication of the irradiance or radiant exposures associated with hazard analysis is given in Table 2.3. The spectral subdivisions chosen correspond to significant subdivisions within the MPE tables. Where a spectral region contains wavelength dependent MPE expressions the chosen wavelengths give the most extreme MPE values. For each spectral region or point, two exposure durations are considered. The 30 000s exposure duration corresponds to the most extreme c.w. exposure. The 1\( \mu \)s
pulse width is not the minimum value contained in the MPE tables, but is suitable for illustrating the typical range of irradiances and radiant exposures. Typical measurement aperture diameters are given to enable the detector power to be calculated. The requirement for infra-red measurements to use different aperture diameters for long (>3 s) and short exposure durations [3] results in the use of different apertures for the single pulse and c.w. conditions. The long wavelength limit in the table is 10.6 \mu m which is sufficient to include all common lasers.

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Exposure duration/ pulse width (s)</th>
<th>MPE irradiance (Wm(^{-2}))</th>
<th>MPE radiant exposure (Jm(^{-2}))</th>
<th>Measurement aperture (mm)</th>
<th>Detector power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>180 - 302.5</td>
<td>30 000</td>
<td>(1 \times 10^3)</td>
<td>30</td>
<td>1</td>
<td>(7.85 \times 10^{-10})</td>
</tr>
<tr>
<td>400</td>
<td>(1 \times 10^6)</td>
<td>(177 \times 10^6)</td>
<td>177</td>
<td>1</td>
<td>139</td>
</tr>
<tr>
<td>401</td>
<td>30 000</td>
<td>0.01</td>
<td>300</td>
<td>7</td>
<td>(7.85 \times 10^{-9})</td>
</tr>
<tr>
<td>700</td>
<td>(1 \times 10^6)</td>
<td>5000</td>
<td>(5 \times 10^3)</td>
<td>7</td>
<td>0.192</td>
</tr>
<tr>
<td>701</td>
<td>30 000</td>
<td>3.2</td>
<td>(96 \times 10^3)</td>
<td>7</td>
<td>(123 \times 10^{-6})</td>
</tr>
<tr>
<td>1400</td>
<td>(1 \times 10^6)</td>
<td>(400 \times 10^3)</td>
<td>0.4</td>
<td>7</td>
<td>15.4</td>
</tr>
<tr>
<td>1401 - 1500</td>
<td>30 000</td>
<td>(1 \times 10^3)</td>
<td>(33 \times 10^3)</td>
<td>3.5</td>
<td>(9.6 \times 10^{-3})</td>
</tr>
<tr>
<td>1401 - 1500</td>
<td>(1 \times 10^6)</td>
<td>(1 \times 10^9)</td>
<td>(1 \times 10^4)</td>
<td>1</td>
<td>785</td>
</tr>
<tr>
<td>1501 - 1800</td>
<td>30 000</td>
<td>(1 \times 10^3)</td>
<td>(33 \times 10^3)</td>
<td>3.5</td>
<td>(9.6 \times 10^{-3})</td>
</tr>
<tr>
<td>1501 - 1800</td>
<td>(1 \times 10^6)</td>
<td>(1 \times 10^{10})</td>
<td>(1 \times 10^4)</td>
<td>1</td>
<td>7854</td>
</tr>
<tr>
<td>1801 - 2600</td>
<td>30 000</td>
<td>(1 \times 10^3)</td>
<td>(33 \times 10^3)</td>
<td>3.5</td>
<td>(9.6 \times 10^{-3})</td>
</tr>
<tr>
<td>1801 - 2600</td>
<td>(1 \times 10^6)</td>
<td>(1 \times 10^9)</td>
<td>(1 \times 10^3)</td>
<td>1</td>
<td>785</td>
</tr>
<tr>
<td>2600 - 10.6 \mu m</td>
<td>30 000</td>
<td>(1 \times 10^3)</td>
<td>(33 \times 10^3)</td>
<td>3.5</td>
<td>(9.6 \times 10^{-3})</td>
</tr>
<tr>
<td>2600 - 10.6 \mu m</td>
<td>(1 \times 10^6)</td>
<td>(177 \times 10^6)</td>
<td>177</td>
<td>1</td>
<td>139</td>
</tr>
</tbody>
</table>

Table 2.3: Irradiance, Radiant Exposure and detector power levels typical for MPE assessments.

It is apparent that the measurement system requires a wide dynamic range to permit operation over the full spectral range. Even within a given spectral region the detector heads require a wide dynamic range. The optical power incident on the detector must be controlled to ensure that non linearity (or ultimately damage) does not occur. The pulse power incident on the detector is a maximum for short pulses. MPE values around and below 1 \mu s have a constant radiant exposure. As a consequence the MPE
pulse irradiance increases linearly with decreasing pulse width. An optical attenuator may be required for short pulse measurements to prevent detector saturation or damage. The attenuator factor must be independent of wavelength, or at least a simple function of wavelength to permit correction of the measured power or energy.

The upper measurement value must include the largest MPE value, but there is little value in increasing the instrument specification to extend measurement ranges to larger irradiance or radiant exposure. It is intended that the instrument should be used as confirmation that a laser system has been properly designed and engineered to prevent exposures exceeding the MPE. Making measurements may result in the detector being accidentally exposed to high irradiances, so a combination of sensitivity and high damage threshold is required. The wide dynamic range required of the detectors must be supported by a wide dynamic range in the signal processing electronics.

Damage, or the possibility of damage must be detected, the user must be warned of this and prevented from making further measurements until the detector has been tested for correct operation.

The lowest power incident on the detector corresponds to the MPE at longest exposure duration. The power may be delivered as c.w. radiation, or may be the average value of a pulse train with pulse width and repetition rate such that the average irradiance determines the MPE. Where the detector power is low it is important that the effects of background radiation and electronic noise can be excluded. This requires careful selection of detector types and the limitation of the electronic bandwidth.

2.2.7 Extended sources

Extended source exposures are associated with sources having a significant diameter, such as expanded laser beams incident on diffusers and some laser diode arrays. An extended source forms an image on the retina. In BS EN 60825:1991 and preceding standards it was assumed that the retinal irradiance controlled damage [20]. Two situations existed;

1. The retinal image was diffraction limited (radiation originating from a point source) and not thermally resolved. (Point source exposure).
2. With larger sources the retinal image would have significant dimensions and would be thermally resolved. (Extended source exposure).

Thermally resolved relates to whether heat flow is backwards, forwards and radially (thermally unresolved) or in the case of a larger spot where heat flow radially from the centre is limited and constrained to directions perpendicular to the image.

For this approach two MPE tables were required, one for point sources and the other for extended sources. Changeover between tables was determined by the angular subtense of the source. The extended source tables were in units of Wm⁻²sr⁻¹ because source radiance is directly proportional to retinal irradiance (assuming no losses through the intervening optical system) [7].

The problem with this approach was that the experimentally determined damage thresholds disagreed with the model of damage threshold controlled by retinal irradiance. The damage threshold was found to vary in proportion to $d_i^{-1}$ rather than $d_i^{-2}$ (where $d_i$ is the retinal image diameter) as would be the case for retinal irradiance controlled damage [20]. The original extended source MPEs did not therefore provide sufficient protection with larger retinal image diameters. A damage threshold proportional to $d_i^{-1}$ can be justified biologically on the basis that heat conducts less well from the centre of a large image than from a small image. Energy absorbed in the centre of a large image must flow further to reach tissue at ambient temperature. Hazard may therefore be regarded as increasing linearly with image diameter. As image diameter increases the incident energy is spread over a larger area (area being proportional to $d_i^2$), therefore the retinal irradiance decreases with the square of image diameter. The combined effect of these controls is the experimentally observed $d_i^{-1}$ relationship.

The new approach suggested by Amendment 2 to IEC 825 [16] and adopted in BS EN 60825:1 (1994) considers three exposure geometries. A point source exposure is assumed for sources subtending angles smaller than $\alpha_{\text{min}}$. Extended sources are split into two categories; those subtending between $\alpha_{\text{min}}$ and 0.1 radian, and large sources subtending more than 0.1 radian. $\alpha_{\text{min}}$ is a time dependent variable which allows for
the fact that for longer exposures the involuntary movement of the eye distributes radiation over a larger area than the spot size to which it is focused. The effective spot size generated by these movements during a point source exposure sets the lower limit for which an extended source is significantly different to a point source exposure. The two limiting values of $\alpha_{\text{min}}$ of 1.5 milliradians for exposure durations shorter than 0.7s and 11 milliradians for exposure durations longer than 10s are based on experimental results. Between these limits a smooth transition is generated using $\alpha_{\text{min}}=2t^{0.75}$ milliradians. Over exposure durations greater than 10s the limited amplitude of the random eye movements prevent further increase in effective spot area.

For extended sources subtending angles less than 0.1 radians the point source MPEs (in terms of corneal irradiance) are multiplied by a factor $C_6$ which is equal to $\alpha/\alpha_{\text{min}}$ where $\alpha$ is the angle subtended by the source at the eye (measurement distances are defined in the standard). An explanation of the derivation of $C_6$ is given by Sutter [20].

For larger sources subtending angles greater than 0.1 radians the original radiance based approach may be used, or equivalently $C_6$ may be set equal to $\alpha^2/(\alpha_{\text{max}}\times\alpha_{\text{min}})$. The changeover at 0.1 radians is not universally accepted. Sutter [20] suggests that the dependency on image diameter remains as $d_{\text{in}}^{-1}$ for images of 2mm diameter (0.12 radians) or greater.

To perform an extended source measurement it is necessary to measure "every single point or assembly of points, necessary to assure that the source does not exceed the MPE for each possible angle $\alpha$ subtended by each partial area, where $\alpha_{\text{min}}<=\alpha<=\alpha_{\text{max}}$."[3]. The practical implication of this is that account must be taken of any "hotspots" (local source areas with higher than average irradiance) rather than averaging over the whole source. If the entire source subtends less than $\alpha_{\text{max}}$ it will only be necessary to measure up to that value of $\alpha$.

To achieve this with a single detector would require a range of lenses and apertures to set the angle of acceptance. Measurements would be made at a range of angles of acceptance, each measurement would require all possible points of the source to be considered. This would be an impractical and time consuming process. An alternative
approach would be to use an image capture and processing system to identify hotspots and perform the appropriate measurements. The more limited dynamic range of imaging detectors when compared to individual detectors might limit the system to identifying hotspots for subsequent detailed examination, or might be overcome using a calibrated means of attenuation to extend the dynamic range.

Extended sources are less frequently encountered than point sources. Rather than attempting to assess extended sources the alternative is to regard them as point sources. This is a restrictive approach, but is better suited to the concept of a general purpose instrument in which advanced functions such as image processing are inappropriate. Example A2-4 of the standard [3] supports this approach and states that this would always overestimate the hazard. This requires some qualification. The basis for the comment is that the hazard of a source decreases linearly with increasing source diameter. For a given source power, the larger source will always be less hazardous. The important qualification is that the detector field of view must be large enough to include the entire source. This guarantees that the whole source power is measured. Otherwise it is possible with large sources, especially those with non-uniform energy distributions, that a large proportion of the total power could be excluded. The assessment would then be insufficiently conservative. If the user did not make a measurement including a hotspot then the true hazard could be missed. In normal point source operation the user is likely to locate the maximum reading successfully because of the rapid changes from background to laser radiation. With an extended source there may be a number of conditions which appear to give a maximum reading and the user may accept one of these in place of the true maximum. Where the field of view encompasses the entire source the effect of hotspots is unimportant. All of the source radiation is included in the measurement. Any hotspots do not cause additional hazard because it is assumed that all of the measured radiation emanates from a point source.

Extended sources may therefore be treated as point sources ($C_e = 1$). This will provide a conservative indication of the hazard so long as the detector has sufficient field of view to include the whole source area.
2.2.8 Measurement distance

Measurement distance is an important consideration for the assessment of extended and divergent laser sources. It is of less relevance when considering collimated beams which do not overfill the measurement aperture. Two measurement distances are commonly suggested [3,20,21,22]; 10cm or 25cm. 10cm corresponds to the minimum distance to which the majority of the population can focus [23]. The inability to focus when viewing closer than 10cm will result in an enlarged retinal image and a reduced hazard.

For MPE assessments it is assumed that viewing is unaided, the limits provided by the standard are "at the cornea of the eye". The use of magnifying optics for close work or binoculars at a distance is by implication excluded from an MPE assessment.

Determination of the appropriate measurement distance requires consideration of the relationship between distance and radiation hazard. Retinal irradiance is independent of the distance between the source and the eye and is controlled by the source radiance [20]. Retinal irradiance damage threshold is proportional to the reciprocal of retinal image diameter [20]. The relationship between source \( d_s \) and retinal \( d_r \) diameters in terms of the focal length of the eye \( a_e \) and distance from the source \( a_t \) is:

\[
\frac{d_r}{d_s} = \frac{a_e}{a_t}
\]

The focal length of the eye \( a_e \) is approximately constant (17mm) [23]. Re-arranging to give an expression for retinal image diameter:

\[
d_r = \frac{d_s \times a_e}{a_t}
\]

For constant ocular focal length and source diameter the retinal image diameter is proportional to the reciprocal of source - eye separation. Retinal damage threshold is proportional to the reciprocal of retinal image diameter, consequently the damage threshold is linearly dependent on source - eye separation for as long as the source fulfills the extended criteria.
Close viewing of extended sources is therefore more hazardous. The most restrictive measurement distance is 10cm (rather than 25cm), or as close as the design of the laser system would permit an eye to approach.

Viewing of divergent sources becomes more hazardous as the viewing distance decreases. This effect is not related to extended sources. A divergent source is re-imaged by the eye to a diffraction limited spot. The irradiance of the retinal spot is proportional to the power entering the pupil. For a uniform divergent beam the diameter is proportional to \( a_1 \) and therefore the irradiance to \( a_1^{-2} \) at any point along it.

The irradiance on the cornea determines the power entering the eye (pupil diameter is assumed to be constant at the worst case value of 7mm). Hazard therefore increases as source - eye separation decreases, with the limiting case being when the entire beam is smaller than the pupil diameter. The effect will be accentuated with non uniform beam cross sections.

Again to obtain the most restrictive case the closest possible measurement distance must be used, subject to a minimum of 10cm. Viewing closer than 10cm would result in an increase in retinal image diameter and a reduction in the hazard.

An exception to the case of measurement at 10cm from the source, or as close as practical would be where the source emitted a converging beam. It is possible that the beam would initially overfill the pupil, but then at some greater distance away from the source the entire beam could enter the eye. This would be a more hazardous condition. For visible lasers it is relatively obvious if the beam is convergent, but for invisible wavelengths it would be necessary to make measurements at several points along the beam. If the readings are constant or decreasing then 10cm is a suitable measurement distance, otherwise the point of maximum reading should be used.

2.2.9 Accuracy of the MPE values

The utility of the current laser safety standards relies on the MPE values accurately predicting safe exposure levels. An MPE value which is set excessively low will inconvenience users, but one which is set too high could result in injury. McKinlay and Harlen [24] compared MPEs to threshold injury data. It was concluded that MPE
values were sufficiently conservative to prevent acute injury in the majority of cases. Some potential problem areas were highlighted:

- UVA exposure of children or aphakics (people with the lens of the eye removed) at the MPE could result in retinal injury because of greater than average optical transmission to the retina.
- Visible wavelength MPEs provide a safety margin only for thermal retinal damage and permanent blue light (photochemical) damage. There was no safety margin for minor, repairable damage.
- Some of the threshold injury data reviewed indicated that the safety factor between damage threshold and MPE was unity or below between 300nm and 315nm.
- The limited information on pulsed laser damage thresholds was raised as a potential problem area. There was insufficient information to determine the accuracy of MPE values for pulse trains.

Since the publication of the work, laser MPE values and standards have been revised. Of the concerns raised by McKinlay and Harlen only the pulsed laser MPEs have been modified in the latest standard [3].

McKinlay and Harlen [24] show that the MPE values in the wavelength range 400nm to 1.4μm have a sufficient safety factor when compared to damage thresholds. Sliney and Dennis [15] discuss a potential radiation safety problem associated with laser diodes operating at 670nm and commonly used in laser pointers. Such laser diodes have a much lower apparent brightness than for example helium-neon lasers. This is because the human eye spectral response is highly wavelength dependent, decreasing from a peak at 550nm to 0.24 of the peak value at 633nm and only 0.032 of the peak value at 670nm. It is suggested that the assumption of an exposure duration limited to 0.25s by the blink reflex might not be appropriate at these wavelengths. Relying on the blink reflex to prevent excessive exposure may provide insufficient protection against retinal damage when the apparent brightness is lower. Despite these concerns, the MPEs are shown to provide sufficient protection so long as an individual does not stare into a non-dazzling 670nm diode laser.
No concerns relating to MPE values for wavelengths longer than 700nm have been raised. Instead the move has been towards relaxation of the limits as more biological damage information has been acquired. Amendment 2 to IEC825:1984 introduced two new step functions between 1.4\(\mu\)m and 2.6\(\mu\)m to more closely follow the biological threshold. In the rationale for the change [16] it was stated that previous safety factors (ratio of damage threshold to MPE) were approximately 2 in the ultraviolet, between 5 and 10 in the visible and retinal hazard region and up to 100 at longer wavelengths. Further future refinement was proposed by adopting smooth exponential curves for the MPE values.

The most recent international laser safety standard [3] contains a revised approach to extended source radiation hazard assessment as described in Section 2.2.7. This was because the approach used in earlier versions of the standard did not provide sufficient protection for some extended sources [20]. Sutter [20] concludes that the present standard [3] still does not properly characterise the risks associated with extended and divergent sources. In some cases the limits are excessively restrictive, in others too lenient.

Modifications to the current standard [3] were proposed by Schumeister [18]. In these it is suggested that the calculation of MPE for pulse trains does not accurately match the damage thresholds. The existing limits assume a repetitive pulse train with constant pulse width, peak power and repetition rate. Schumeister proposes expressions which are suitable for more complex exposure conditions. The current status of these proposals is unknown, communication with a member of the IEC and CENELEC committees [25] suggested that they were too radical too be agreed upon by all members and were unlikely to be adopted.

The uncertainty regarding the accuracy with which current MPE values predict damage threshold arises from the need to determine exposure limits from a restricted body of damage data. Lasers operating at uncommon wavelengths or exposure durations are least likely to have damage thresholds characterised accurately by the MPE values. Despite the concerns, in the absence of reports of injury by levels of radiation below the MPE is likely that the current levels are approximately correct.
The importance of the statements in the standard that "MPE values .... should not be regarded as precisely defined dividing lines between safe and dangerous levels" and "exposure to laser radiation shall be as low as possible" is highlighted.

2.2.10 Summary

Standards documents present Maximum Permissible Exposure levels for laser radiation. These represent levels to which the majority of the population may be exposed without adverse reaction, but exposure should be minimised as far as reasonable practical. A classification scheme is presented in the international laser safety standard. This indicates to a laser user what degree of hazard control measures are required. Analysis of the MPE limits given in the standard is essential in determining the specifications of measurement equipment for radiation hazard assessment purposes. The detailed analysis provided information on the assessment of c.w. and pulsed lasers, the requirements for resolving pulses, the power and energy ranges associated with MPEs, approaches to extended source assessment and on the distance from a laser source at which a measurement should be performed. Possible accuracy limitations in the MPE values were also discussed.

The most significant finding of the work was the confirmation that energy is the most important measurand for radiation hazard assessment. It was shown that it is sufficient to measure the energy of short (<18μs generally) pulses without resolving the pulse width. For longer pulses the pulse power becomes significant, but this may be derived from the pulse width and pulse energy. Measurements of c.w. laser radiation may be based on the total energy received during a measurement period. An instrument capable of energy measurement is therefore suitable for c.w. and pulsed laser radiation hazard assessments.

Having obtained some of the fundamental requirements for laser radiation hazard assessment it is appropriate to examine the measurement process and available equipment in greater detail.
2.3 MEASUREMENT EQUIPMENT FOR HAZARD ASSESSMENT

2.3.1 The use of measurements in laser radiation safety

The emphasis of the work on laser radiation measurements for safety purposes described in this thesis is on assessing whether a given source exceeds the MPE rather than performing classification. MPEs are the fundamental determinant of the radiation hazard presented by a source. Accessible Emission Limits (AELs) used in determining the class of a laser product are derived from a combination of MPE values and anticipated viewing and exposure duration conditions. AEL assessments require that the use of an optical instrument, such as binoculars be considered. By contrast, MPEs are for exposure at the cornea (or skin) and therefore exclude optical instruments. AEL assessments require a wider range of detector optics to successfully simulate the potential range of viewing conditions.

The safety of the user is an important aspect of instrument design. There are differences in the rationale behind making measurements for MPE assessment and AEL calculation. An MPE assessment is made to verify that the system has been correctly designed to avoid hazardous exposures. The assessment is performed to provide supporting evidence that engineering controls are effective. Measuring AELs for classification implies that in some cases the user could be exposed to radiation from Class 3B or Class 4 lasers. It is conceivable that the user could be unaware of the radiation hazard until the classification results were available. An instrument for performing classification therefore carries the risk of the user being unintentionally exposed to hazardous radiation.

It was anticipated that there would be four categories of user for the instrument. The first type of user would model the entire laser system to predict the levels of accessible radiation. Measurement would be required to verify the predictions. The second type of user would regard the modelling of the laser system to be unnecessarily complex. Controls would be adopted on the basis of knowledge and experience. Measurement would be required to verify that sufficient controls had been adopted. The third user would typically have responsibility for safety, but with little specific understanding of the hazards associated with lasers. Measurements would be required as part of the job.
function to check that the system presented no hazards. Finally a more general user would be interested in performing a routine assessment of all laser (and other) systems as part of a quality and safety system.

Sliney [26] casts doubt on the need to perform any measurements, but the statement is made in relation to intrabeam hazards. The justification for not making measurements is that direct exposure to a laser beam is invariably hazardous. On this basis it is suggested that measurements would only be required to classify the direct laser beam. This argument overlooks the fact that the extreme and localised hazard presented by a laser beam means that it is rarely accessible. Hazards exist at the point of utilisation. In industrial applications the hazard could be scattering of laser radiation from the workpiece, or in entertainment applications when a single beam is split into many low power beams as part of a display. Such situations require a means of verifying that the accessible radiation levels do not exceed the MPE. Calculation may be of use to locate conditions and areas of greatest hazard, but the complex nature of the laser beam interaction is likely to make any model of the system complex or inaccurate. A better approach is to use initial calculations of the MPE followed by a suitable measurement. Measurements may be made in many positions and under many operating conditions to verify the overall safety of the system.

Only a limited amount of guidance is available on making measurements for laser radiation hazard assessment. Sliney [26] discusses laser radiometry and calorimetry in a general sense with limited emphasis on hazard assessment. Types of detector and instrument, calibration and common measurement pitfalls are described. Other papers have been published [27,28,29], these cover laser radiation measurement with an emphasis on hazard assessment. All of the published work has the disadvantage that the detail relates to American rather than international standards. As a result the guidance on measurement techniques is of use, but the detail is less relevant and could cause confusion if applied to hazard assessment for international standards.
2.3.2 Standards for laser radiation measurement equipment

Information on the requirements for laser radiation measurement equipment is provided by various standards. Both ISO/CEN and IEC/CENELEC publish relevant standards. The primary standard is BS EN 61040:1993 (equivalent to IEC 1040) which specifies the requirements for laser power and energy measurement detectors, instruments and equipment [30]. This document defines terminology appropriate to laser power and energy measurement equipment, accuracy of instrumentation, performance tests to verify accuracy and details of the information required in instrument operation instructions. The standard is primarily concerned with definitions, requirements and test methods for instrumentation. Instrument and detector accuracy are based on a classification system, providing an overall class for the instrument or detector on the basis of contributions from several specified sources of uncertainty. The bias of the standard is towards high power thermal detectors and it is therefore not completely applicable to hazard assessment equipment. Each class designation provides an estimate of the percentage measurement uncertainty. To determine the appropriate class for an instrument, test requirements are defined in BS EN 61040:1992. Error sources in radiometers and photometers are defined in detail by a CIE publication [31] as a means of comparing instruments. This information illustrates the wide range of environmental factors which may affect a measurement.

The implications of each of the test requirements in BS EN 61040 for instrument operation is discussed below:

• Change in responsivity with time.
  This is determined by the change in detector responsivity with time and the stability of the electronic circuitry. The choice of detector and the choice of circuit configuration and component types are therefore important.

• Non-uniformity of responsivity over the detector surface.
  This is a function of the detector. If optical components external to the detector are used then these will have an impact on overall spatial non-uniformity.
• Change in responsivity during irradiation.
  This is predominantly a function of detector stability.

• Temperature dependence of responsivity.
  This is a function of the detector and to a more limited extent the electronic circuits. Compensation for temperature dependency may be necessary as part of an instrument design. The final dependency of responsivity on temperature will then be determined by the accuracy of the temperature correction function. BS EN 61040 requires the instrument to operate within the range of ambient temperature 0°C to 40°C.

• Dependence of responsivity on angle of incidence for non-polarised radiation.
  This is a function of the detector and any additional optics. Increasing the angle of acceptance to ensure accurate assessment of extended sources will reduce the significance of this factor.

• Dependence of responsivity on radiant power or energy (non linearity).
  This is an important factor, determined primarily by the detector non-linearity but to a more limited extent by the non-linearity of any signal processing electronics.

• Wavelength dependency of responsivity.
  This is a function of the detector and any additional optics which are fitted. Correction for variations in responsivity with wavelength may be performed by the instrument. In such situations the final dependency of responsivity on wavelength will be determined by the accuracy of the wavelength correction function.

• Polarisation dependence of responsivity for linearly polarised radiation.
  This is controlled by the detector and any additional optical components used.

• Errors of averaging with respect to time of repetitively pulsed radiation.
  This will be a function of detector operation and the operation of electronic averaging, pulse stretching or integration circuitry.
• Zero drift.
The significance of zero drift may be minimised by the use of a background radiation subtraction function. Zero drift is then combined with variations in background radiation and eliminated as part of a measurement.

• Calibration uncertainty.
This is largely dependent on the accuracy of the instruments used to perform a calibration. The instrument design must be such that all functional aspects are covered by a calibration.

It is apparent that the detectors play a fundamental role in overall instrument accuracy. Where the instrument is to be hand held, uncertainties associated with human issues such as detector alignment may limit the overall measurement accuracy. An instrument accuracy of Class 10 in which "the sum of the absolute amounts of the individual uncertainties shall not exceed 20%, the root sum square uncertainty shall not exceed 8%" was selected as the minimum acceptable instrument accuracy for hazard assessment purposes.

Additional detail on measurement terminology and test methods for laser beam parameters is provided by ISO11554 [32]. This standard concentrates on measurement methods for laser power and energy measurement, and the temporal characteristics of pulsed lasers. It complements the BS EN 61040 coverage of instrumentation requirements. ISO11554 defines sample rates, detector time constants and number of pulses required for measurement of laser beam parameters. Definitions of beam power and pulse parameters are provided. The contents of a measurement test report are stated, along with the format of results presentation. As with the BS EN 61040 the requirements are more relevant to high power laser instrumentation.

ISO11145 [33] provides definitions of the vocabulary relating to lasers and laser related equipment. There is some overlap in definitions between ISO11145 and ISO11554. In these cases the definitions are compatible, but with minor differences in phrasing. ISO11145 covers laser terminology more generally without the emphasis on detectors or measurement equipment provided by ISO11554.
2.3.3 Limitations of commercially available instrumentation

A wide variety of instrumentation is available commercially for measurements of laser power or energy. Given that a laser radiation hazard assessment is fundamentally a measurement of laser power or energy it is possible to consider the use of laser power or energy meters for the specific task of radiation hazard assessment. Examination of commercially available instrumentation reveals that such equipment is not well matched to the requirements of laser radiation hazard assessment. Shortcomings in terms of the instrument performance and in the suitability for user requirements make it inappropriate to use standard instrumentation in most cases. Some of the major limitations are discussed below. No specific instruments will be identified, the observations apply equally to most commercially available equipment. Further information on the range of commercially available instrumentation is available from manufacturer's literature and from laser buyer's guides [34,35].

- The detectors are usually designed with large diameter apertures to facilitate alignment in the laser beam. This is contrary to the requirement in the standard to use one of four defined circular measurement apertures (or one of three if lasers operating at wavelengths longer than 100μm are excluded, see Table 2.3). Making an MPE measurement over a larger diameter aperture than specified may introduce errors because any small, intense parts of a radiation pattern are averaged over the larger area. This underestimates the true hazard which would be revealed by using the smaller, correct aperture diameter.

- Sections 2.2.4 and 2.2.5 demonstrate that there are specific requirements for the measurement of pulsed laser radiation for hazard assessment. Manufacturer's documentation indicates that laser power measurement instrumentation is either incapable of pulsed laser measurements, or displays only the average power of the incident pulse train. This will cause the true hazard of a pulse train consisting of low repetition rate, intense pulses to be underestimated. The majority of instruments designed for pulse resolution do not have a sufficiently wide operating range of pulse widths and repetition rates to be of general use for scanned or pulsed laser radiation hazard assessments.
• The instrument display is not matched to the information requirements of the user. Measured values are displayed in units of power or energy. The user must perform calculations to convert to irradiance or radiant exposure and must calculate the appropriate MPE value from the standards. This is a process that users find intimidating and which is prone to error.

• Instruments have limited data storage facilities. It is necessary for the user to transcribe individual measurement results which provides opportunities for error. In some instruments an interface to a computer may be provided. This permits data storage, but limits the portability of the instrument.

• Instruments are generally designed for laboratory rather than field use. Long battery life is not therefore treated as necessary; a mains power supply is frequently used. This, combined with a lack of design for portability make the instruments inconvenient for field use.

2.3.4 Task specific instrumentation

There has been little documented work relating to the design of instruments to perform or assist in laser radiation hazard assessment. Sliney [26] commented on the lack of an instrument designed specifically for radiation hazard analysis on a variety of lasers. The most versatile instrument developed for laser radiation hazard assessment was described by Silberberg [36,37]. This instrument was designed to determine whether visible laser radiation exceeded Class 1 as defined by the FDA standard [38]. At visible wavelengths the FDA standard presented identical limits to the IEC825:1984 standard. The temperature stability of the meter and detector head was subsequently verified by Royston et al. [39]. Software was used to control much of the meter operation and the calculation process.

A silicon detector was used, this had a 7mm diameter aperture built in. A filter was included to give the detector a flat spectral response between 450nm and 650nm. If required an optical attenuator could be added to extend the measurement range. It was necessary to set a switch indicating that the attenuator was in use. This represents a potential source of user error. The meter functioned with c.w or pulsed radiation,
but the user had to select the mode prior to a measurement. For pulsed laser radiation the minimum measurable pulse width was 18µs.

In c.w. mode the meter measured the incident energy over ten seconds. At the end of the measurement the energy was displayed, followed by the time at which the Class 1 AEL was exceeded. If the AEL was not exceeded then the measured value was used to extrapolate and determine at what time it would be exceeded.

In pulse operation the energy was integrated over two timescales. One was the total energy over ten seconds, the other was the energy over 255µs. Energy over 255µs was measured repeatedly, albeit with some dead time whilst one set of data was digitised and the integrator reset. The short period integrator was intended for recording pulse energy. Two pulse modes were provided. In basic pulsed mode a measurement was made over ten seconds with both integrators operating. Up to 255 pulses (short term integrator results) are captured. The circuit was designed to prevent overflow if the pulse repetition rate was higher than 26Hz. In effect a maximum of 255 pulses are sampled by increasing the time between sampled pulses in proportion to the number of pulses measured. This reduced the memory requirements. Total energy was measured accurately using the long period integrator. The alternative pulsed mode, termed "each pulse" was intended to measure the energy and duration of 255 sequential pulses (so long as the repetition rate was sufficiently low). In both pulsed modes the display at the end of the measurement process indicated the time at which the Class 1 AEL was exceeded, or by extrapolation, would be exceeded.

Two additional modes were provided; background and calibration. Background readings were made before each measurement and the output of short and long term integrators recorded after a ten second measurement period. Subsequent measurements of laser radiation then have the background values subtracted. Background values are stored in memory until a new background measurement is taken, or the power turned off. Although it is convenient to make only one background measurement this will degrade the accuracy of the instrument. In many environments, moving the detector to take subsequent measurements will change the
background. Errors will be introduced if the user forgets to perform a new background measurement.

Calibration was performed using an external $75\mu$W source. The outputs of long and short term integrators following a ten second measurement are recorded and used to scale subsequent measurements. This approach has the advantage of providing a frequent check on meter and detector performance. A calibration had to be performed each time the meter was switched on, calibration factors were not stored after power was disconnected. This would be a significant inconvenience for field use. Calibration source stability could also be impaired by frequent movement and operation.

The assessment technique for pulsed lasers was limited. Relatively few pulses were sampled (a maximum of 255, typically 180 for pulse repetition rates between 20Hz and 2kHz). In high repetition rate pulse trains less than 0.1% of all pulses may be recorded. Total energy was still recorded accurately, but there was a very high risk that if pulse energy or peak power varies within the pulse train that this might not be recorded. For hazard assessment purposes this is very significant as a single more intense pulse could take the pulse train from non hazardous to hazardous.

A minimum measurable pulse width of $18\mu$s was specified. It was stated that the response speed of the unbiased photodiode introduced this limit. For some pulsed lasers this is sufficiently fast, but a significant number generate shorter pulses. Even some scanned display lasers when generating large patterns at a distance from the laser can generate pulses shorter than $18\mu$s over a 7mm diameter aperture. It would be essential that the user was aware of this limitation, and was able to determine whether the incident laser radiation consisted of pulses shorter than $18\mu$s. Without detailed examination using an oscilloscope connected to the detector output this would be difficult.

A more recent development was described in a paper relating to the radiation safety of surveying lasers [40]. Communication with the author provided some further details of the instrument [41]. The instrument was designed for assessing the optical hazard of c.w and scanning (pulsed) lasers operating at 633nm and between 700nm and 900nm in the infrared. A 7mm aperture was used to define the measurement aperture on the
photodiode. To eliminate the effects of background radiation a second photodetector was used. This was not exposed to laser radiation and allowed a continuous compensation for ambient illumination to be made. In many cases this would be a very elegant means of removing background contributions. It could become difficult to use if the laser radiation was scanned or emitted from a diverging source because ensuring that the reference detector received only background light with no laser radiation becomes impractical. It would be essential that the user was aware of this situation or the measured value would be excessively low. Using two detectors was also an economical disadvantage.

The user had to manually select the spectral region and whether the radiation was pulsed or c.w.. Both of these decisions are subject to user error which would affect the validity of the assessment. The meter displayed the measured power, a set of purpose designed nomograms, based on IEC 825 and BS 4803 were used to determine the safe exposure time to the measured radiation. This approach meant that the instrument was not made obsolete by changes to the standards, new nomograms could readily be prepared for current standards. The use of nomograms was an improvement over requiring the user to perform calculations, but it would be intimidating to non-mathematical users and user errors would be possible.

2.3.5 Summary

Measurement of laser radiation is required in many practical situations where it is not possible to accurately model and calculate the levels of laser radiation to which people could be exposed. Only a limited amount of information has been published on making measurements for hazard assessment purposes. Standards for laser radiation measurement equipment exist but these apply to more general laser radiometry rather than instruments for radiation hazard assessment. Examination of commercially available laser power or energy measurement equipment reveals that it is not well suited to laser radiation hazard assessment. Two previous examples of instruments designed specifically for laser radiation hazard assessment are discussed. It was found that neither addressed the full range of issues involved in laser radiation hazard assessments.
The next section considers the detectors available for laser radiation measurement. It is important to establish that limitations of detectors are not responsible for constraining the pulse measurement abilities of laser radiation measurement equipment.

2.4 DETECTORS

2.4.1 Introduction

Detector performance is fundamental to the performance of a laser radiation measurement instrument. In this application the most important aspects of detector performance were the spectral response, the frequency response (for pulse response), the noise performance, the damage threshold and the spatial uniformity of responsivity. It was essential that the detectors were compact and relatively low cost. Cooling, either by liquefied gas or thermoelectric means was impractical because of portability and current consumption issues. Table 2.4 summarises the types of detectors capable of uncooled operation and suitable for the power levels encountered in hazard assessment. The performance data is typical rather than being specific and is based on room temperature operation.

Photoconductor and thermistor detectors have the disadvantage of requiring a bias voltage to measure the change of resistance caused by absorbed radiation. This makes c.w. measurements difficult; the small change in voltage originating from the absorbed radiation is swamped by the constant bias voltage. The use of a bridge configuration in which one detector is active and the other acts as a reference has the disadvantage of extra cost. Such detectors were excluded in preference to those which generated a signal directly. A range of photodiodes are available for operation over ultraviolet, visible and near infrared wavelengths. Photodiodes are suitable for c.w. measurements and also have the short response time necessary for pulsed laser measurements. At longer infrared wavelengths (to 10.6μm) a pyroelectric detector may be used for pulsed measurements, a thin film thermopile is appropriate for c.w. measurements. Using these two detectors is more cost effective than using a photoconductor detector and avoids the problems associated with the use of a bias voltage.
<table>
<thead>
<tr>
<th>Detector type</th>
<th>Spectral Range</th>
<th>Response time</th>
<th>Notes</th>
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</thead>
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<td>200 - 400nm</td>
<td>Not specified</td>
<td>Photodiode</td>
</tr>
<tr>
<td>Gallium Phosphide (GaP)</td>
<td>190 - 550nm</td>
<td>5μs</td>
<td>Photodiode</td>
</tr>
<tr>
<td>Gallium Arsenide Phosphide (GaAsP)</td>
<td>190 - 680nm</td>
<td>1μs</td>
<td>Photodiode</td>
</tr>
<tr>
<td>Silicon (Si)</td>
<td>190 - 1100nm</td>
<td>0.1μs</td>
<td>UV Enhanced Photodiode</td>
</tr>
<tr>
<td>Silicon (Si)</td>
<td>350 - 1100nm</td>
<td>3ns</td>
<td>PIN Photodiode</td>
</tr>
<tr>
<td>Germanium (Ge)</td>
<td>600 - 1900nm</td>
<td>0.1μs</td>
<td>Photodiode</td>
</tr>
<tr>
<td>Indium Gallium Arsenide (InGaAs)</td>
<td>800 - 1700nm</td>
<td>5ns</td>
<td>Photodiode</td>
</tr>
<tr>
<td>Lead Sulphide (PbS)</td>
<td>1 - 3μm</td>
<td>100μs</td>
<td>Photoconductor</td>
</tr>
<tr>
<td>Lead Selenide (PbSe)</td>
<td>1 - 4.5μm</td>
<td>1μs</td>
<td>Photoconductor</td>
</tr>
<tr>
<td>Indium Arsenide (InAs)</td>
<td>1 - 3.6μm</td>
<td>1μs</td>
<td>Photodiode</td>
</tr>
<tr>
<td>Mercury Cadmium Telluride (HgCdTe)</td>
<td>2 - 12μm</td>
<td>0.1μs</td>
<td>Photoconductor</td>
</tr>
<tr>
<td>Thin Film Thermopile</td>
<td>1 -13μm (IRTRAN 2 window)</td>
<td>40ms</td>
<td>Spectral response determined by window transmittance</td>
</tr>
<tr>
<td>Pyroelectric</td>
<td>1 -13μm (IRTRAN 2 window)</td>
<td>&lt;1ns (no response to constant illumination)</td>
<td>Spectral response determined by window transmittance, response time by external amplifier</td>
</tr>
<tr>
<td>Thermistor</td>
<td>1 - 13μm (IRTRAN 2 window)</td>
<td>&lt; 1ms</td>
<td>Spectral response determined by window transmittance</td>
</tr>
</tbody>
</table>

Table 2.4: Summary of potential detector types
2.4.2 Photodiodes

2.4.2.1 Mode of operation

Photodiodes rely on the absorption of incident photons to generate electron-hole pairs (charge carriers) in a semiconductor material. A photodiode is constructed by forming a PN junction in a semiconductor material (where P and N refer to doped semiconductor material with excess holes and electrons respectively). Charge carriers are separated by the in-built electric field associated with the PN junction, possibly assisted by an external bias voltage. Between the P and N materials there then exists a depletion layer. In the depletion layer all charge carriers, whether thermally or optically generated, are separated by the action of the internal field which creates a region devoid of charge carriers. Applying a reverse bias increases the width of the depletion layer. A forward bias narrows the depletion layer, eventually permitting current to flow across the junction.

Absorption of a photon with sufficient energy in the depletion layer generates an electron-hole pair. These are separated by the electric field and permit a single charge carrier to flow in an external circuit. The energy of a photon is inversely proportional to wavelength, photons at shorter wavelengths having greater energy. This accounts for two aspects of photodiode operation; the loss of responsivity above a certain wavelength and the decrease of responsivity with decreasing wavelength throughout the operating spectral region.

The long wave cut-off wavelength is determined by the bandgap energy of the semiconductor material, only incident photons with energy in excess of the bandgap energy can cause the generation of charge carriers. Below the cut-off wavelength the responsivity decreases with decreasing wavelength. Photon energy is inversely proportional to wavelength, consequently at a constant optical power the number of photons decreases at shorter wavelengths. So long as the photodiode is operated under conditions where each absorbed photon produces one electron-hole pair the number of charge carriers generated by a given optical power is inversely proportional to the wavelength of the incident radiation. All photodiodes have a peak value of responsivity at a given wavelength. This peak is determined by the interaction of the
increasing photon flux at constant power as wavelength increases and the decreasing probability of charge carrier generation as the cut off wavelength is approached.

The physical structure of the photodiode determines the actual spectral response by modifying the theoretical spectral response. A photogenerated charge carrier pair can only contribute to an external current once it reaches the depletion layer. Photodiodes are designed to ensure that the majority of photo-generated charge carriers are created in the depletion layer. If this is not the case, charge carriers must first diffuse to the depletion layer. This takes longer than the separation of charge carriers generated in the depletion layer because of the low field strengths outside the depletion layer. The delay in reaching the diffusion layer increases the probability of the electron hole pair recombining and reduces the probability of the photogenerated carrier contributing to the external photocurrent.

Absorption depth is proportional to wavelength [42]. Photodiodes are optimised for long wavelength response if the depletion layer penetrates deep into the device. Such a device must be relatively thick and capable of withstanding significant reverse bias. Applying an external reverse bias to the photodiode extends the depletion layer through the depth of the device and ensures efficient collection of long wavelength photogenerated carriers [43]. Conversely to achieve good short wavelength responsivity the junction should be fabricated close to the photodiode surface because photons are absorbed in a very short distance [44]. One approach to this is the Schottky photodiode, the junction is formed between a thin metallic layer and a doped semiconductor substrate [45]. The depletion layer is immediately beneath the metallic layer which is designed to be transparent to the wavelengths of interest.

Photodiode responsivity is temperature sensitive. This is a function of the temperature dependence of absorption coefficient [42]. At wavelengths approaching the long wave cut-off, responsivity has a positive temperature coefficient. This is illustrated for silicon by Budde [46], for Schottky GaAsP devices by Wilson and Lyall [47] and for Germanium and InGaAs by Boivin [48]. At long wavelengths the responsivity is limited by the decreasing absorption coefficient of the semiconductor. The rate of decrease of absorption coefficient becomes rapid as the bandgap energy is approached.
Increasing temperature increases the absorption coefficient, the high sensitivity of responsivity to absorption coefficient causes a significant increase in responsivity with temperature.

At short wavelengths photodiodes may exhibit a small negative temperature coefficient. This is also associated with the increase in absorption coefficient with temperature. Short wavelengths are absorbed close to the surface of the device. Unless the device has been optimised for operation at short wavelengths the photo-generated carrier collection becomes inefficient close to the device surface. An increase in absorption coefficient will increase the proportion of photons absorbed close to the surface and will therefore decrease the device efficiency. Between the two spectral extremes photodiode responsivity is almost independent of temperature. The temperature sensitivity of responsivity is more pronounced if the photodiode open circuit voltage is measured rather than the current [46].

2.4.2.2 Photodiode noise

Two sources dominate the noise generated by a photodiode; these are shot noise and Johnson noise [46]. Shot noise is generated by the dark current associated with the finite shunt resistance [46]. High values of shunt resistance and minimal reverse bias reduce shot noise. Shot noise has power proportional to the measurement bandwidth (white noise) and is predicted by the following equation:

\[ I_s = \sqrt{2 \times e \times \Delta f \times (I_d + I_p)} \]

where; \( I_s \) is the r.m.s. shot noise current, \( e \) is the electronic charge, \( \Delta f \) is the noise bandwidth, \( I_d \) is the dark current and \( I_p \) is the photo current

Johnson noise originates as the thermal noise of the shunt resistance [46]. This is also a white noise source and is predicted by:

\[ I_t = \sqrt{\frac{4 \times k \times T \times \Delta f}{R_{SH}}} \]

where; \( I_t \) is the r.m.s. thermal noise current, \( k \) is Boltzmann's Constant, \( T \) is the absolute temperature, \( \Delta f \) is the noise bandwidth, \( R_{SH} \) is the shunt resistance
Additional, less significant noise sources exist. 1/f noise may become significant at low frequencies [49]. This source has a power which is inversely proportional to frequency. 1/f noise is associated with contact and surface effects but has no exact expression [49]. Careful device design and manufacture reduce the significance of 1/f noise. Quantum noise is generated by the random process of variations in photon arrival rate [49].

Noise sources are assumed to be independent and therefore the total noise ($I_n$) based on the two most significant sources is determined by:

$$I_n = \sqrt{I_s^2 + I_t^2}$$

### 2.4.2.3 Photodiode types for specific spectral regions

Unlike the thermopile and pyroelectric detectors, photodiodes have an inherent spectral sensitivity which restricts operation to a specific spectral region. For ultraviolet radiation measurements SiC, GaAsP, GaP and ultraviolet enhanced silicon devices are suitable. It has been found that some ultraviolet enhanced silicon photodiodes do not have stable responsivity when exposed to ultraviolet radiation [50,51,52,53,54]. GaP and GaAsP devices are found to be better in this respect, and have a greater linear range [45]. Silicon photodiodes have the additional disadvantage of a wide spectral response which increases the effect of background light on the measurement. SiC, GaAsP and GaP devices have intrinsic long wave cut offs between 400nm and 600nm which reduces the significance of background light. It is possible to use filters to limit the spectral response of the silicon devices, but the filters may suffer degradation by ultraviolet radiation [47].

Silicon photodiodes are suitable for operation over visible and near infrared wavelengths to 1.1μm. Limiting operation to wavelengths shorter than the peak of responsivity (approximately 950nm) reduces the sensitivity of responsivity to temperature. At infra-red wavelengths beyond the long wavelength cut-off of silicon photodiodes alternative materials are required. Germanium and InGaAs are suitable
between 1.6\textmu m and 1.9\textmu m. Germanium is the more established technology, but has inferior performance compared to InGaAs [48,55]. This is manifested as a lower shunt resistance, slower response speed and greater temperature sensitivity of responsivity. InGaAs has responsivity largely independent of temperature. Beyond 2\textmu m Indium Arsenide photodiodes are suitable, but alternative detector technologies become more appropriate for the intended application.

2.4.2.4 Photodiode damage mechanisms and thresholds

It is important that the detector output remains linear throughout the expected range of incident power and energy. Minor overloads should not cause the detector to become non-linear. Greater overloads may cause detector saturation, but the detector output must not decrease or the true measured power could be underestimated. Table 2.5 summarises references related to photodiode damage threshold and mechanisms.

The differences in damage threshold presented by the various investigators is a consequence of the differing definitions of damage threshold, different types of target material or device and different methods of illumination. The information contained in references 99 to 101 is based on information from manufacturers and is provided for completeness. Generally a maximum permissible current is specified by the manufacturers. This implies that failure of the connecting leads may occur before detector degradation for c.w. exposures.

Krueer et al. [56] presented damage threshold data for a silicon PIN photodiode at 1.06\textmu m and 694.3nm and proposed a thermal model for the damage. It was shown that the thermal model accurately matched experimentally determined damage thresholds. A thermal damage mechanism explains the temporal and spectral dependency of damage threshold. Two temporal regimes exist. During short pulses the heat flow through the device away from the volume of absorption is minimal. Damage occurs when the volume of material in which absorption occurs is raised to some critical temperature. This is a localised effect. Long pulses at a given wavelength raise the detector bulk to a thermal equilibrium as absorbed and dissipated powers reach balance. Short pulse damage is characterised by a constant energy threshold and long pulse damage by a constant power threshold. An intermediate
The region between the two regimes exists. The changeover between the regimes is determined primarily by the thermal conductivity of the material.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Damage threshold</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>57</td>
<td>0.45Jcm$^{-2}$</td>
<td>1.06μm, 60ps. Visible damage</td>
</tr>
<tr>
<td></td>
<td>1.6Jcm$^{-2}$</td>
<td>1.06μm, 5ns. Damage threshold</td>
</tr>
<tr>
<td></td>
<td>1.5Jcm$^{-2}$</td>
<td>580nm, 2μs. No visible damage</td>
</tr>
<tr>
<td></td>
<td>11Jcm$^{-2}$</td>
<td>580nm, 2μs. Increase in sheet resistance.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>All results relate to irradiation of n type silicon samples</td>
</tr>
<tr>
<td>58</td>
<td>2.4Jcm$^{-2}$</td>
<td>1064nm, 10ns. Typical for surface melting</td>
</tr>
<tr>
<td></td>
<td>2.9Jcm$^{-2}$</td>
<td>1064nm, 10ns. Typical for increase in dark current</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Results summarised from various photodiode types.</td>
</tr>
<tr>
<td>59</td>
<td>0.54Jcm$^{-2}$</td>
<td>1.06μm, 10ns. First symptom was increase in dark current in CCD arrays.</td>
</tr>
<tr>
<td>56</td>
<td>31Jcm$^{-2}$</td>
<td>1.06μm, 34ns. Loss of responsivity of PIN photodiode.</td>
</tr>
<tr>
<td></td>
<td>65Jcm$^{-2}$</td>
<td>1.06μm, 17ns. Surface melting</td>
</tr>
<tr>
<td></td>
<td>10 000Wcm$^{-2}$</td>
<td>1.06μm, &gt;0.01s. Surface melting.</td>
</tr>
<tr>
<td></td>
<td>2Jcm$^{-2}$</td>
<td>694.3nm, 19ns. Loss of responsivity of PIN photodiode.</td>
</tr>
<tr>
<td></td>
<td>1.5Jcm$^{-2}$</td>
<td>694.3nm, 25ns. Reduction of photocurrent in solar cell.</td>
</tr>
<tr>
<td></td>
<td>40Jcm$^{-2}$</td>
<td>694.3nm, 1ms. Loss of responsivity of PIN photodiode.</td>
</tr>
<tr>
<td></td>
<td>10 000Wcm$^{-2}$</td>
<td>694.3nm, &gt;0.01s. Surface melting.</td>
</tr>
<tr>
<td>60</td>
<td>5Jcm$^{-2}$</td>
<td>1.06μm, 22ns. Phototransistor photocurrent unaffected.</td>
</tr>
<tr>
<td>61</td>
<td>0.4Jcm$^{-2}$</td>
<td>1064nm, 10ns. CCD damage threshold</td>
</tr>
<tr>
<td></td>
<td>2Jcm$^{-2}$</td>
<td>1064nm, 10ns. Photodiode array damage.</td>
</tr>
<tr>
<td>62</td>
<td>6Jcm$^{-2}$</td>
<td>Reduced long wavelength photocurrent in silicon solar cell</td>
</tr>
<tr>
<td>63</td>
<td>2.5Wcm$^{-2}$</td>
<td>Maximum average power for 1mm diameter InGaAs</td>
</tr>
<tr>
<td>64</td>
<td>100Wcm$^{-2}$</td>
<td>Damage threshold for PIN InGaAs</td>
</tr>
<tr>
<td>65</td>
<td>64Wcm$^{-2}$</td>
<td>Maximum average power for 1mm diameter GaP</td>
</tr>
</tbody>
</table>

Table 2.5: Summary of photodiode damage thresholds

The wavelength dependency of absorption coefficient affects the damage threshold. Radiation which penetrates deeply into a device (longer wavelengths) will dissipate the energy of short pulses over a greater volume than short wavelengths which are absorbed closer to the surface. Pulses of short wavelength radiation are therefore
found to have lower damage thresholds. For c.w. or long pulses the spectral dependency of damage threshold disappears because the detector reaches thermal equilibrium irrespective of the absorption depth.

Watkins et al. [58] investigated the electrical performance of various laser damaged photodiodes. It was found that surface morphological damage occurred at lower energies than electrical degradation. Of the electrical parameters the dark current was found to be the most sensitive to damage. Degradation in electrical parameters was found to have an abrupt threshold. These two findings were in agreement with the work of Kruer et al. [56]. For practical applications an abrupt transition to damaged state is preferable to a gradual degradation because damage may then be more easily detected.

Watkins et al. [58] investigated the effect of multiple shots on the same site of the detector. Damage thresholds were found to fall by a factor of ten at the most for electrical and morphological damage between single shots and a train of 3000 shots. Multiple shot exposures showed the same pattern of damage symptoms as single shot exposures.

When comparing detector damage thresholds to the approximate range of radiant exposure relevant to hazard analysis shown in Table 2.3 it is apparent that a significant safety margin exists between MPE values and damage thresholds. Photodiodes are not used at the longer wavelengths where higher radiant exposures are encountered. Damage threshold information for other than silicon photodiodes was difficult to obtain, it may be assumed that the damage will be thermal in nature and therefore will be influenced by the thermal conductivity and melting point of the semiconductor. The sensitivity of pulse damage threshold to wavelength will exist because all photodiodes exhibit spectral dependency of absorption coefficient. The thermal conductivity of silicon, germanium, GaP and SiC are within an order of magnitude and with the exception of germanium, melting points are in the range 1000°C to 2000°C [66]. Damage thresholds for long duration exposures should therefore be within an order of magnitude. Short pulse damage thresholds may also be comparable, but depend on the absorption coefficient of the semiconductor to determine the volume into which pulse
energy is dissipated. The thermal conductivity of InGaAs is dependent on the relative fractions of the three components [67]. Most compositions of InGaAs have a thermal conductivity approximately a factor of ten lower than that of silicon and can be assumed to be more susceptible to thermal damage.

The abrupt damage threshold for electrical degradation is an advantage because it reduces the probability of damage not being observed. All information on damage to silicon photodiodes indicated that electrical degradation was associated with an increase in dark current. This is a simple parameter to measure and could form the basis of a damage detection function. The tendency of manufacturers to give a maximum current raises concerns about the rating of the wire used to connect the photodiode chip to the connecting wires. In use it is prudent to consider some method of limiting photocurrent under optical overload conditions.

2.4.3 Pyroelectric detectors

2.4.3.1 Mode of operation

Certain materials exhibit a pyroelectric effect; an increase in the material temperature causes a change in the surface charge of the material. This change in surface charge may be detected by depositing electrodes normal to the polarisation vector of the material. A change in surface charge may be detected as a voltage or current by an external circuit. Charge is generated by changes in detector temperature rather than the final steady state temperature. This prevents the use of pyroelectric detectors for c.w. measurements (unless the incident radiation is chopped) but permits very fast operation [68]. The fact that the crystal does not have to reach thermal equilibrium allows the pyroelectric detector to respond faster than other thermal detectors and yet still have the wide spectral response characteristic of thermal detectors. Pyroelectric detectors have a maximum temperature of operation, referred to as the Curie Temperature. If a crystal is heated above this temperature the polarisation is lost and the pyroelectric effect is no longer observed. It is possible to make the change reversible on cooling by applying a bias voltage to the detector, or by doping the crystal [46].
An ideal pyroelectric detector would generate an output current which is independent of the modulation frequency of the incident radiation. Physical limitations cause the output current to become frequency dependent at low and high frequencies. A practical pyroelectric detector may be approximated as having a first order roll off below a low frequency breakpoint, termed the thermal breakpoint, and a first order roll off above a high frequency breakpoint, termed the electrical breakpoint. Both thermal and electrical properties determine the detector performance.

The thermal breakpoint frequency is independent of external components and is determined by the thermal capacity of the pyroelectric element and the thermal resistance between the pyroelectric element and ambient [69]. Reducing the heat loss from the detector element reduces the thermal cut off frequency. This can be achieved by evacuating the detector enclosure and mounting the detector element using a material of low thermal conductivity. The penalty of reducing the heat loss from the detector is that the detector is less able to withstand high energy pulses without suffering thermal damage. A conflict of requirements exists between the need for extended low frequency response and immunity to damage.

The minimum pulse repetition rate at which a pyroelectric detector functions satisfactorily is a function of the thermal breakpoint frequency. The primary effect of the decrease in low frequency responsivity is that the detector output stabilises to have a zero d.c. component. This is manifested by the area of the current / time plot of detector output being equal above and below zero. The peak value of the output pulse train is highest when radiation is first incident on a detector and decreases to a steady value as the element reaches thermal equilibrium. A pyroelectric detector could not therefore replace a photodiode because the average irradiance would appear to be zero.

A second problem associated with the limited low frequency response is that if the width of individual pulses, or the duration between pulses becomes a significant proportion of the thermal time constant then pulse distortion will occur. This arises because a constant input irradiance cannot in practice cause a constant increase in element temperature. Instead the detector element approaches a thermal equilibrium...
and the rate of temperature increase decreases. The output current therefore decreases towards zero. Similarly, at the end of a pulse the rate of decrease in element temperature is initially a maximum but decreases towards zero as the element approaches the ambient temperature. The output current therefore initially has a maximum negative value and decreases towards zero.

For low frequency operation (<1kHz) a black coating on the detector surface can increase the responsivity by increasing the absorption of incident radiation [70]. At higher frequencies the slower energy transfer through a thick coating degrades the overall detector responsivity. A thin metallic coating on the detector is used to enhance the absorption of radiation whilst preserving rapid energy transfer to the pyroelectric element [68].

The spectral response of a pyroelectric detector is controlled by the wavelength dependency of crystal absorption, black coating absorption and window transmission. Common pyroelectric materials such as SBN (strontium barium niobate), TGS (triglycine sulphate) and LiTaO₃ (lithium tantulate) are transparent at visible and near infra-red wavelengths, becoming strongly absorbing from 2μm to 1000μm (with some fluctuation in the absorption coefficient around 10μm) [46,69]. In this application operation at wavelengths longer than 1.5μm was required. It was necessary to consider the use of a coated detector to extend the short wavelength spectral response. Two options are available [70]; a relatively thick black coating (as used on a thermopile detector) gives a high and near constant absorption from approximately 300nm to 30μm. Alternatively thinner metallic coatings can be applied to the front and rear faces of the detector. These coatings extend the spectral response into the ultraviolet. A lower responsivity is obtained with a metallic coating than if a thick black coating was used. At longer wavelengths the absorption in the metallic coating becomes less significant, absorption by the crystal dominates. Consequently the fluctuations in responsivity around 10μm are apparent for at thin metallic coating, whereas they are almost completely suppressed with a thick black coating [71]. The advantage of a thin metallic coating for this application is that detector response time is not increased and pulse energy may be integrated external to the detector.
The responsivity of pyroelectric detectors is slightly dependent on temperature. For a typical detector the variation is less than $+0.2\%^\circ C$ [72] and is governed by changes to the pyroelectric coefficient [46].

2.4.3.2 Pyroelectric detector noise

The principal noise source associated with the pyroelectric detector is the Johnson Noise generated by the parallel resistance representing the loss conductance ($R_L$) [69]. Temperature noise will also be present, but for detectors of practical thickness will be insignificant in comparison to the Johnson Noise [69]. The expression for Johnson Noise in pyroelectric detectors is equivalent to that applying to photodiodes:

$$I_t = \sqrt{\frac{4kT\Delta f}{R_D}}$$

where; $I_t$ is the r.m.s thermal noise current, $k$ is Boltzmann's constant, $T$ is the absolute temperature, $\Delta f$ is the noise bandwidth, $R_D$ is the loss resistance.

Expressing the noise in terms of current is appropriate since it was intended that the detector would be used in current mode. A large value of loss resistance (small loss conductance) is necessary to minimise noise.

2.4.3.3 Pyroelectric damage thresholds and mechanisms

Thermal damage mechanisms affect pyroelectric detectors. It is necessary to differentiate between the effects of overload on the detector crystal and on any coating or electrode which is present.

Two electrode configurations are used in pyroelectric detectors; face electrode and edge electrode. Face electrode detectors have the pyroelectric axis normal to the absorbing area of the detector. Electrodes for measuring charge are applied to the front and rear surfaces of the detector. The electrode on the front surface of the detector doubles as an absorbing coating. Edge electrode detectors have the pyroelectric axis parallel to the absorbing area. Electrodes for measuring charge are applied to two opposite detector sides.
Theoretically edge electrode configuration is preferable [69] because it minimises detector capacitance by reducing the electrode area and increasing the electrode separation. This increases response speed and reduces noise at high frequencies. The reduction in capacitance is of little significance in practice where the stray package and external capacitances swamp the detector capacitance. There is little performance benefit from using edge electrode configuration and the face electrode configuration has the advantage that the front surface electrode also enhances short wavelength responsivity. All of the pyroelectric detectors considered for the instrument were of the face electrode type.

The electrode configuration is a significant factor in determining the detector damage mechanism [68,71]. In face electrode configuration the maximum temperature rise of the electrode determines the damage threshold for short pulses. Longer duration pulses cause damage by the bulk heating of the detector crystal. The distinction between long and short pulses for electrode damage relates to the time taken for absorbed energy to be transferred from the electrode to the detector crystal. Metallic coatings are designed to preserve the detector pulse response by providing very rapid thermal transfer. Typically 90% of the absorbed energy would be transferred within 400ps [68]. For edge electrode detectors the maximum temperature of the detector crystal determines the damage threshold for long and short pulses unless a coating is applied to modify the spectral responsivity. Differences between edge and face electrode configuration are only significant for pulses shorter than 10µs [68]. For longer duration pulses the presence of a face electrode becomes insignificant because energy is transferred rapidly to the bulk of the detector.

It is found that the face electrode configuration has a lower damage threshold to short pulses than edge electrode configuration. This is despite the metal electrode having a larger permissible temperature rise than pyroelectric crystals such as LiTaO₃ (1000°C versus 500°C). The electrode is much thinner (10nm) than the absorption depth of the pyroelectric crystal (10µm at 10.6µm) [68]. The energy absorbed per volume is therefore much greater in the coating. It is important to note that the higher damage threshold associated with edge electrode configuration applies only if the detector is
uncoated. If a coating is applied to enhance the responsivity then the damage thresholds and mechanisms for the two configurations become similar.

For an uncoated edge electrode detector and all configurations where the incident pulse width is sufficient to make the coating irrelevant the detector crystal will be damaged by overload. Crystal damage is defined as physical degradation rather than loss of the pyroelectric effect. For materials such as TGS and SBN physical degradation occurs at higher temperatures than the material Curie temperature. Loss of the pyroelectric effect caused by temperatures exceeding the Curie temperature is not regarded as damage because it is a reversible effect. The Curie temperature is an important operational parameter because it defines the maximum detector temperature which can be permitted without detector saturation. Materials such as TGS (Curie temperature 49°C) or SBN (Curie temperature 115°C) will have a lower maximum measurable pulse energy than LiTaO₃ (Curie temperature 618°C) [49].

Published work on damage to pyroelectric materials [73,74] discusses two damage mechanisms; cracking and thermal decomposition (charring). It is found that cracking usually occurs at lower energies than thermal decomposition, but if the energy is spread uniformly over the detector then thermal decomposition occurs first. The cracking process is associated with thermally induced stresses in the material and is therefore more pronounced with non-uniform irradiation where a thermal differential exists on the detector surface. In common with thermal damage thresholds in other detector types [56], a pulse width dependency of damage threshold is observed in pyroelectric detectors. Short pulses (short being defined in relation to the time for the whole crystal to reach thermal equilibrium) have a constant energy damage threshold, independent of pulse width. Short pulse damage can be defined in terms of surface temperature because it is the thermal gradient arising from absorption at the surface which introduces stresses to the crystal. Under uniform illumination where surface stresses are minimised, higher surface temperatures are permissible before cracking occurs. For longer pulses the damage threshold energy increases and shows a dependency on pulse width. The increase in damage threshold occurs because heat has time to flow to the bulk of the crystal, resulting in decreased thermal gradients. Actual damage thresholds correspond to the temperature for thermal degradation of the
crystal. Mounting the detector on a heatsink of high thermal conductivity improves the power handling ability, but at the expense of degrading the low frequency performance [46,75].

Manufacturer's data specifies a maximum average power of 0.2W for the detector with best low frequency performance (lowest thermal conductivity to substrate). Over the sensitive area of the detector this corresponds to approximately 60 000Wm$^{-2}$ [72]. This is safely in excess of the MPE values.

For a detector fabricated from LiTaO$_3$ the energy required to raise the detector by 500°C, thereby approaching the Curie Temperature, is 1.6Jcm$^{-2}$ (16 000Jm$^{-2}$) [71]. This provides a safety margin for normal operation, even in the spectral range 1500nm to 1800nm.

The threshold for electrode damage is given as 200Jm$^{-2}$ for a 1ns pulse [71] and 60Jm$^{-2}$ for a 100ps pulse [68]. The coating damage threshold varies as $t^{0.5}$ [71]. On this basis the Curie temperature energy limit of a LiTaO$_3$ detector (16 000Jm$^{-2}$) dictates the maximum pulse energy for pulse durations longer than approximately 6μs. The electrode temperature energy limit dictates the maximum pulse energy for shorter pulses.

Over the spectral range 2.6μm to 10.6μm the pyroelectric detector damage thresholds are greater than the MPE values. The safety margin between MPE value and damage threshold decreases to a minimum of a factor of two at 1ns. Detector damage by shorter pulses is avoided because the MPE values become constant irradiance below 1ns, pulse energy therefore decreases with decreasing pulse width. MPE values are higher between 1.5μm and 2.6μm and the damage threshold for the electrode would be exceeded for pulses shorter than 2.5μs (1.5μm $< \lambda < 1.8\mu m$) and 25ns elsewhere.

For MPE assessments of laser radiation generated by a CO$_2$ laser (10.6μm) which is anticipated to be a major application for the pyroelectric detector head, detector damage will not be a problem. Optical attenuation is required for MPE assessments of short pulse lasers between 1.5μm and 2.6μm, especially over the spectral range 1.5μm to 1.8μm. Short pulses may also bring the risk of detector cracking if the irradiance is
not uniform. Focusing of the laser radiation should therefore be avoided throughout the spectral range of the pyroelectric detector. Some additional safety margin will be provided by reflection and absorption losses in the detector window.

2.4.4 Thermopile Detectors

2.4.4.1 Mode of operation

Thermopile detectors utilise the heating effect of absorbed incident radiation to generate a temperature difference between the two junctions of thermocouples. The cold junction of each thermocouple is maintained at ambient temperature by a heatsink and the hot junction is heated by the incident radiation. Several thermocouples are connected electrically in series to increase the responsivity of the detector. A thermopile may be constructed from discrete wire thermocouples, but to increase the response speed and responsivity thin film techniques are used [46]. Only thin film thermopiles had sufficient responsivity for this application.

Thin film thermopiles are constructed by evaporating metals such as bismuth and antimony onto a suitable substrate (such as Mylar) using a mask to define the thermocouples [46]. Often these are formed in a circular pattern, the central junctions being covered with a black coating and exposed to incident radiation and the outer junctions being shielded from incident radiation. The outer junctions are in good thermal contact with the detector case to provide a constant ambient reference temperature. Absorbed radiation causes heating of the central thermopile junctions. A thermally resistive substrate is required to minimise heat loss by conduction. Radiation incident on the detector causes a thermal differential across the thermocouples proportional to the absorbed power. By the Seebeck Effect a voltage is generated across the detector output which is proportional to the incident power. The discrete nature of the sensitive elements of a thermopile detector can result in spatial non-uniformity if the radiation is incident on a small spot rather than the whole sensitive area.

In the majority of cases the spectral transmission of the window defines the overall spectral response of the detector. The black coating is chosen to have a near flat
spectral response [76,77]. Increasing the coating thickness enhances radiation absorption but can reduce the response speed [70]. Response speed is limited by the slow thermal diffusion through the black coating and the thermal mass of the thermocouple junctions. By reducing the mass of the junctions and relying on direct absorption of radiation, devices with response times of 20\mu s have been reported [78].

It is necessary to measure the open circuit voltage of the thermopile using a high input impedance amplifier. This prevents significant current flow through the detector. A current flowing through the detector would act in opposition to the heating effect of absorbed radiation and would cool the junctions (Peltier Effect), thereby introducing a systematic error to the measurement [46].

Ambient temperature affects the responsivity of thermopile detectors. This is independent of the wavelength of the incident radiation. The manufacturers of a typical device give a value for the temperature sensitivity of -0.4%/°C [79].

2.4.4.2 Thermopile detector noise

A thermopile detector acts as a pure resistance, the most significant noise source is the Johnson noise of this resistance [79]. In terms of voltage, the Johnson noise is given as:

\[ V_n = \sqrt{4 \times k \times T \times \Delta f \times R_t} \]

where; \( V_n \) is the r.m.s. Johnson noise voltage, \( k \) is Boltzmann's Constant, \( T \) is the absolute temperature, \( \Delta f \) is the noise bandwidth, \( R_t \) is the detector resistance.

A secondary noise source is temperature noise. This arises from the fluctuation in temperature of the detector element because of fluctuations in the rate at which heat is transferred from the detector to the surroundings [49]. Temperature noise has a power proportional to measurement bandwidth (white noise).
2.4.4.3 Thermopile damage mechanisms and thresholds

The damage mechanism applicable to thin film thermopiles is thermal overload causing the melting of the mylar substrate [80]. For pulses much longer than the thermopile thermal time constant (including c.w. operation) the manufacturers specify an average power limit of 1000Wm\(^{-2}\) [79]. For short durations (<100ms) the maximum permissible irradiance is 10 000Wm\(^{-2}\) [80]. If the incident pulse is significantly shorter than the detector thermal time constant the substrate will not reach an equilibrium temperature. Damage by melting of the substrate is therefore less likely to be the limiting factor. Instead damage to the black absorbing coating caused by excessive rates of energy absorption will occur. Thermal damage to the coating will occur before the absorbed energy can be conducted to the volume of the detector. Drawing a parallel with short pulse damage to pyroelectric detectors such a damage mechanism will be dependent on pulse energy rather than irradiance [68]. Since the thermal time constant is typically 40ms [79] the changeover between constant power and constant energy damage thresholds may be assumed to occur for pulses with width between 1ms and 100ms. Limited information is available on the damage threshold of black paints. Preston [81] gives a limit of 0.1J in 1ms spread over 78.5mm\(^2\) (equivalent to 1270Jm\(^{-2}\)) for Nextel paint.

A thin film thermopile would require some attenuation of the incident radiation to ensure that it was not damaged at exposures close to the MPE. The MPE for c.w. exposure is equal to the recommended maximum detector irradiance (1000Wm\(^{-2}\)). Short pulses where the coating determines the damage threshold have some safety margin in most of the infra-red region. An exception is between 1500nm and 1800nm where the MPE is 10 000Jm\(^{-2}\) and exceeds the limit suggested in the previous paragraph for Nextel paint. A small safety margin will be obtained by reflection and absorption losses in the detector window, but this is not sufficient alone.
2.4.5 Summary

From the range of available detector types photodiodes, pyroelectric detectors and thermopile detectors have been selected as being suitable for the measurement task. Photodiodes are appropriate for measurements of ultraviolet, visible and near infrared (to 1.5\(\mu\)m) radiation. At longer wavelengths the MPEs become larger and it is possible to use alternative detectors. Pyroelectric detectors are suitable for measurement of pulsed lasers whereas thermopile detectors are suitable for c.w. and low pulse repetition rate laser measurements. The basic mode of operation for each detector was described along with the noise performance, damage mechanisms and damage thresholds. It was apparent that detectors did not represent a fundamental limitation to the measurement of laser radiation for hazard assessment. All of the detector types had specific limitations, but these could be overcome by appropriate instrument design. The need to use at least three detectors to cover the full range of laser wavelengths indicates that a degree of modularity will be required in the instrument.
2.5 HUMAN FACTORS IN LASER RADIATION SAFETY

2.5.1 Introduction

The previous sections have considered many of the technical aspects of measurements for laser radiation hazard assessment. A complete study of the requirements of the measurement process must also include the needs of the instrument user. The first section considers the suitability of the laser safety standards for the user. Since the standard forms the basis of laser radiation hazard assessments any shortcomings in the use of the standard should be considered in the instrument design. Requirements for human-computer interfacing are then considered and compared to the implementation on commercially available instruments.

2.5.2 Suitability of the standards for the users

Results from two surveys of groups with an interest in laser safety revealed limitations in the suitability of the standards for users. Vassie et al. [82] investigated the attitude of a sample of laser manufacturers, laser users and inspectors from the UK Health and Safety Executive (HSE) towards the laser safety standard. At the time of the survey BS7192:1989 was in force. Subsequent modifications to the standard have not addressed the limitations found by the survey.

Laser manufacturers expressed concerns about the technical complexity of the standard. This was felt to limit the usefulness of the document to an experienced laser safety officer. It was felt that guidance was required with various aspects of the standard, in particular MPEs, AELs and NOHDs.

Laser users found the standard technically complex and the presentation of information insufficiently structured. It was felt that support was required in the calculation of MPEs, AELs and NOHDs and power measurement techniques.

Health and Safety Executive inspectors did not raise concerns about the content of the standards, but noted that some aspects of the standard were open to interpretation and required further detail. Even experienced inspectors commented on the need for a facility to simplify the calculation of parameters such as the MPE.
Raymond and Tyrer [83] undertook a more detailed evaluation of education and training needs in laser safety. A specific question related to the role of BS EN 60825. It was found that the use of the standard for guidance on calculations was typically considered the most problematic. Laser safety course provision (in and prior to 1993) was felt by the majority of respondents (50%) to provide insufficient training on the calculation of parameters such as MPE. When asked about the importance of topics which should be included on training courses approximately 90% felt hazard calculations were important or very important and approximately 55% sought information on laser radiation measurement equipment. A desire for such information suggests the respondents were dissatisfied with their current knowledge and the available equipment.

2.5.3 Aspects of user interfacing

Groups with an interest in MPE assessments include laser manufacturers, laser users and Health and Safety Inspectors. Knowledge and experience of laser radiation measurement and MPE calculations vary between and within these groups. It is essential that equipment for MPE assessments is designed with the user requirements in mind. Frequently the personnel performing the assessment are not laser radiation measurement specialists who may lack the expertise to appreciate the limitations of the equipment available.

A critical part of the instrument is the user interface, especially if the users are unfamiliar with the measurement process. Equipment operation must be straightforward to understand and designed to lead the user through the process. The opportunity for human error needs to be minimised. If possible human error should be prevented by designing the system to prevent an operator committing the error [84]. Human errors could affect the measurement process in three ways; errors could be made when entering data, when making the measurement of laser radiation or when interpreting the measurement results.

Data entry errors can be largely eliminated by cross checking all user entered data. Where the user may be unsure of what should be entered, appropriate values should be suggested or help provided. Data entry should be in a form relevant to the task [85].
In this situation an example would be the entry of laser wavelength directly in nanometres rather than metres. Human error in selecting inappropriate measurement equipment can be addressed by individually coding each element of the instrument. During an assessment each element can then be automatically identified. A suitable choice of elements can be verified by cross checking the selection with the wavelength and exposure duration data entered by the user. Coding would include each detector head, the aperture used and any neutral density or spectral filters in use.

The requirements for the user interface mean that at the very least a text display is required, along with a numerical data entry capability. A keyboard for data entry is preferable to all other methods such as dials, levers or switches [84]. Operator speed can be increased and error rates reduced. Improvements such as alphanumeric data entry and a graphics display would further enhance the user interface.

Human related measurement errors could occur as a consequence of detector misalignment or selection of inappropriate measurement equipment. The significance of such errors can be expected to decrease as the user becomes more experienced [84]. Designing detectors with a wide angle of acceptance reduces the sensitivity to misalignment. The effect of misalignment is also minimised by making multiple measurements to establish the worst case. An instrument designed to simplify the assessment process facilitates making repeated measurements.

Interpretation of measurement results is assisted by proper design of the user interface. It was anticipated that the measurement results would be used in two ways. The first would be during the initial stages of an assessment where several measurement locations were compared to locate the worst case. Rapid evaluation of the hazard at each location would be required. Once the worst case had been located the second measurement function would be required. A quantitative reading would be used to define the actual hazard. For rapid, qualitative comparisons a moving pointer type display is optimum, for quantitative measurements a counter type display is superior [84]. To ensure optimum matching of the instrument to the task both types of display are required. To avoid the possibility of user errors when transcribing measurement
results data storage is useful. This would permit transfer of results directly to a computer for long term storage.

Shneiderman [85] discusses the many aspects of human-computer interfacing. The relevant interaction styles considered included a range of menu structures and command languages. Examples of the different interaction styles are provided and the benefits of different structures for different applications are discussed. The advantages of the menu structure for inexperienced users were highlighted. Information was also provided on the design of error and help messages. Eight "golden rules" are given which relate to the design of dialogues for human-computer interaction.

• Strive for consistency.
  Ensure that the names and shortcuts used for commands are the same as identical ones in other applications. Keep a common style to dialogues throughout the application. Menus should be written to group functions logically.

• Provide shortcuts for experienced users.

• Provide informative feedback.
  Whilst the instrument is performing a task which provides no intrinsic indication to the user a message should be displayed stating the activity.

• Design dialogues to yield closure.
  Organise actions into groups with a beginning, middle and end. Providing a structure such as this gives users a feeling of achievement at the end of each group.

• Provide simple error handling.
  Design the system to prevent serious user error, detect errors and offer simple and comprehensible means for recovering from the error. It is important that error messages do not condemn the user by using negative terms. Supporting text should be brief and specific. Indicating the permissible range of values is helpful where appropriate. If an error occurs then all of the data entered
by the user should not be abandoned, instead the user should be returned to the appropriate stage and given the opportunity of correcting the error.

- Permit easy reversibility of actions.
  As far as it is practical, allow the user to reverse an action. This reduces the potential for user anxiety and encourages exploration of software functions.

- Support internal locus of control.
  Operators should feel in control of the system. Surprising system actions, tedious data entry requirements, difficulty in extracting information and inability to make the system perform an action cause user dissatisfaction. Menu choices should be clear and specific, with predictable effects.

- Reduce short term memory load on the user.
  Humans have limited ability to store information in short term memory. The need to remember commands or data should be minimised, and reminders (as part of a help function) provided. Menu driven software is useful so long as the menu structure is sufficiently intuitive to avoid the need to remember paths through the menu tree.

The user interface of instruments such as the Labmaster and Fieldmaster (two popular instruments manufactured by Coherent Inc. and consisting of a meter unit and a range of detector heads) is suited to the basic task of laser power or energy measurement. A combination of analogue (bargraph or moving needle) and digital displays are provided. The requirements for laser radiation hazard analysis are not met by this basic display. As described in Section 2.2.3, the display is not in appropriate units. All calculation must be performed manually. Individual elements of the instrument are automatically identified and the user is warned if an inappropriate selection of detector and measurement range is made.

The two instruments designed for laser radiation hazard assessment (Section 2.2.4) had basic user interfaces which did not provide guidance to a user, or detect user errors such as selecting a pulsed mode for a c.w. assessment.
2.6 SUMMARY

The MPE is the fundamental determinant of radiation hazard. Concepts such as the laser classification relate to whether a given laser system can present a radiation hazard under certain viewing and exposure conditions. Laser classification applies the MPE to the specific conditions. The classification scheme does not always remove the need for laser radiation measurements, there remains a requirement for measurement based hazard assessment. Typically measurement is used to supplement an initial calculation of hazard and to prove that a given hazard control strategy is effective.

Standards documents are available which define permissible exposure levels to laser radiation. The laser safety standard has been subject to change as the state of knowledge has increased, and further change is still possible. Analysis of the standards is essential to determine the technical specifications required of equipment for laser radiation hazard analysis. The important finding of this analysis was that incident energy over an exposure duration determines the radiation hazard. Pulse width is significant for long pulses (generally greater than 18 μs) which means that such pulses must be temporally resolved. For shorter pulses it is only necessary to measure the pulse energy, where the pulse repetition rate is greater than 56 kHz it is only necessary to measure the total energy. Only two exceptions to this occur, for these it is only necessary to resolve individual pulses at low repetition rates (below 674 Hz) but pulse width is required for the calculation of the MPE of low repetition rate pulses. The inconvenience of this may be minimised by resolving the pulse widths in common use and obtaining the pulse width of shorter pulses from the user. An instrument capable of energy integration can then be used for all laser radiation hazard analysis. Not needing to resolve short pulses permits important relaxation of the instrumentation bandwidth specifications. Existing commercially available instrumentation does not conform to these measurement requirements.

Literature relating to laser radiation measurement equipment has been reviewed. Standards exist for such equipment, the documents have some relevance to the design of radiation hazard evaluation equipment but are more generally biased towards measurement of laser beam characteristics. Commercially available laser power and
energy measurement equipment is not suited to the requirements of laser radiation hazard assessments. Specific limitations have been described which limit the applicability of such equipment. These limitations may be partially overcome by expert users, but remain problematic for more general users. A limited amount of prior work exists on laser radiation hazard evaluation equipment. No previous work was found to address the detailed and unique measurement requirements nor to thoroughly consider the requirements of users.

From the wide range of available detector types, photodiodes, pyroelectric and thermopile detectors were selected as being most suitable for the application. The main theoretical aspects of each detector type were examined. It was apparent that detectors were available to perform the measurements required for laser radiation hazard analysis as highlighted by the analysis of the standard. This showed that it would be possible to design an instrument better matched to the technical requirements of the measurement problem. The need to use several detector types indicates that a degree of modularity would be required in the instrument.

Two main areas where human factors are important in the process of laser radiation hazard assessment have been described. These are in the usability of the standards documents for different groups of users and in the user interface design of instrumentation. Several limitations in the standards were revealed. All categories of users from novice to expert had difficulty interpreting and using the standards. Difficulties related to the need to perform calculations and the lack of information on measurement techniques were also raised. These issues strengthen the case for the development of instrumentation adapted to laser radiation hazard assessment. Information on the design of the user interface was obtained. It is important that the user interface is properly designed in order to minimise the occurrence of user error. The various sources of user error are considered.

It was apparent that both technical requirements and user requirements would have to be addressed in the instrument strategy. Implementing the calculation of MPE and comparison to the measured value by the instrument would address many of the problems encountered when attempting to interpret and apply the laser safety standard.
3 INVESTIGATION OF THE MEASUREMENT TASK

3.1 INTRODUCTION

In Section 2.3.3 it had been determined that commercially available laser power and energy measurement equipment had limitations for the specific task of laser radiation hazard assessment. To substantiate this work and demonstrate situations in which general purpose instrumentation could be successfully used two practical examples of measurement for laser radiation hazard assessment were investigated.

Two important laser applications were chosen for study. These intentionally represented contrasting approaches to laser safety. The first application was the industrial use of a high power CO₂ laser for material processing, the second was the use of visible (argon ion and krypton ion) lasers for entertainment purposes. Each application requires that human exposure to levels of laser radiation exceeding the MPE is prevented but the methods of ensuring this differed.

In the industrial application high laser powers are used. The entire beam path is enclosed and relatively few people are present whilst the laser is in operation. The suppliers of such systems are generally knowledgeable of the hazards. In an industrial situation a responsible attitude is taken towards safety, helped by the obvious hazards of lasers capable of cutting through sheets of material. By contrast display laser systems use much lower powers (but still hazardous to the eye) laser, but the radiation is intentionally unenclosed. Large numbers of people are present whilst the system is in operation. The audience cannot be expected to have any appreciation of the hazards of laser radiation. It is also found in practice the display laser operators do not always regard safety as a primary concern.

Instrumentation was selected to be representative of that which was known to be in use for hazard assessment. Where detailed data on the radiation hazards was required, additional, purpose built equipment was used. The radiation hazard implications of the measured results are discussed in each of the case studies. The findings of the case studies are combined with the work of Chapter 2 to summarise the specifications of task specific instrumentation.
3.2 STUDY OF TYPICAL APPLICATIONS

3.2.1 High power CO₂ laser material processing

3.2.1.1 Introduction to Laser Machining

Laser machining is a non-contact thermal process. The laser energy may be used for one-dimensional machining (drilling), two-dimensional machining (cutting) or three-dimensional machining (milling) [86]. Material removal occurs by the melting, vaporisation or direct degradation of the volume to be removed [86]. Materials which can be machined by lasers include metals, ceramics, plastics and wood. Carbon Dioxide and Nd-YAG lasers are most frequently used in industrial laser material processing because of the availability of high output powers with a high electrical to laser energy conversion efficiency (several kilowatts with efficiency to 10% for CO₂ lasers) [86]. The high laser powers required for material processing imply the use of Class 4 lasers. To ensure that the material processing machines pose no significant radiation hazard during operation the machine as a whole must be Class 1. This is achieved by engineering design, primarily by enclosing the beam delivery path and optics. It is important that the enclosure is capable of withstanding fault conditions, or where this would be inflexible and restrictive, that there is some means of detecting fault conditions. Radiation hazards may also exist where laser radiation does not couple into the workpiece (unintentional reflections) or from radiation generated by the processing operation.

3.2.1.2 Description of the system

The installation studied during the investigation used a 2kW CO₂ laser with a movable beam delivery system mounted on a gantry above the workpiece. A computerised system controls the movement of the gantry and the cutting head, the workpiece remains stationary. The gantry is capable of moving on rails over the length of a 10m by 3m bed. The large area bed permits one workpiece to be loaded whilst another is processed. The system is used predominantly to cut mild steel plates of thickness between 4mm and 10mm. Galvanised mild steel, stainless steel and aluminium are also processed. Laser marking is used to identify workpieces for subsequent assembly. The laser is capable of generating pulses between c.w. and 200μs duration at repetition
rates up to 1kHz. When cutting, a c.w. power of 1820W was used, marking was performed using a power between 85W and 90W. The pierce of the workpiece prior to cutting used the laser in pulsed mode with an average power of between 360W and 400W.

3.2.1.3 Experimental method

For the hazard assessments the laser was operated in c.w. mode. A calibrated detector and meter (Coherent Labmaster and LM10 head) were used to measure the levels of laser radiation scattered and reflected from the process zone. The LM10 detector head is a thermopile type with a spectral response from 0.3 µm to 10.6µm. The inability of the LM10 to resolve pulses was unimportant because the laser was used in c.w. mode.

At 10.6 µm the Maximum Permissible Exposure (MPE) is 1000 Wm² [3]. The LM10 head has an active area of $2.84 \times 10^{-4}$ m². An irradiance of 1000 Wm² corresponded to a reading on the Labmaster of 0.284 W. The resolution of the instrument was 1mW and the maximum power 10W. The Labmaster and LM10 head were therefore suitable for measuring the power associated with the MPE in this application.

An initial investigation of the spatial profile of the scattered radiation revealed a maximum directly behind the laser - material interaction point. The angle of detector elevation above the workpiece was significant. Maximum irradiance was measured at low angles. As the angle increased the irradiance decreased. This general situation applied to the cutting of the four metals investigated.

The computer was programmed to cut a raster pattern in the test workpiece. The positioning of the detector relative to the raster pattern ensured that one cut line was centrally away from the detector. This exposed the detector to the maximum irradiance located in the initial investigation. To ensure that the detector field of view was sufficiently wide to receive radiation from the full raster area the heatsink and shield combination was removed from the front of the detector. The Labmaster meter measured the power incident on the detector at one second intervals over the cut duration and displayed the results as a plot of power versus time. The power measured by the instrument was proportional to irradiance at the detector. Sheets of
mild steel (4mm thick), galvanised steel (3mm thick), stainless steel (2mm thick) and aluminium (2mm thick) were cut.

3.2.1.4 Results

The measured values of peak power (irradiance) are shown for each material in Table 3.1. Emissivity values for mild steel, galvanised steel and aluminium for 10.6μm radiation at 20°C are included in the table. It was assumed that the emissivity of galvanised steel was dominated by the mild steel. For opaque solids:

$$\varepsilon = 1 - R_0$$

Where $\varepsilon$ is the emissivity and $R_0$ the reflection at normal incidence.

A low value of emissivity implies a high reflectivity. The single values contained in Table 3.1 simplify the complex situation existing during material processing but provide a guide to comparative material behaviour. Emissivity values for a given material at a given wavelength are functions of temperature and surface condition [87]. An increase in temperature increases the emissivity and therefore decreases the reflectivity. As absorbed laser radiation causes local heating the reflectivity decreases, resulting in an increase in the rate of energy absorption. This has the effect of positive feedback and results in a rapid increase in the energy absorbed by the material. Duley [87] illustrates this effect with mild steel, for a constant single laser pulse width (0.5μs) the measured reflectivity remained constant at approximately 0.85 for energy densities less than 5 Jcm⁻² before decreasing rapidly to approximately 0.20 at an energy density of 20 Jcm⁻² (data at greater energy densities was not provided). Above the threshold of 5Jcm⁻², heating by the early portion of the pulse caused increased absorption of the remainder of the energy.

<table>
<thead>
<tr>
<th>Metal type</th>
<th>Peak power measured (mW)</th>
<th>Emissivity (ε) [87]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild steel</td>
<td>20</td>
<td>0.04</td>
</tr>
<tr>
<td>Galvanised steel</td>
<td>20</td>
<td>0.04</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>160</td>
<td>Not given</td>
</tr>
<tr>
<td>Aluminium</td>
<td>190</td>
<td>0.019</td>
</tr>
</tbody>
</table>

Table 3.1 : Measurement and emissivity data for test materials
Surface condition, for example the presence of roughness or an oxide layer increases emissivity at 10.6μm. This may have a more limited effect during cutting where the surface takes only a small part in total radiation absorption. Oxide formation during heating and complex effects such as absorption and thermal transfer by plasma and radiation trapping in the cut hole will also increase the total energy absorption [87].

It was found that the profile of irradiance versus time had a form similar to Figure 3.1 for all materials. Only the points marked (+) on Figure 3.1 corresponded to measured values. The profile of the curve was derived from observation of several raster cuts in each material, but does not represent absolute measured values. The results shown in Figure 3.1 are for aluminium which gave the greatest reflected powers. Each peak point corresponded to the laser cutting away from the detector, but being at the end of the raster nearest to the detector. The highest peak occurred when the laser was cutting away from the detector along the detector central axis. Troughs corresponded to the times when the laser was at the end of the raster furthest from the detector and cutting parallel to the detector face. The final peak corresponded to the laser cutting to the finish and passing directly in front of the detector. The power measured in a trough was only slightly higher than the level of background radiation. Background radiation was significant because energy conducted from the cut heated the metal sheet which therefore emitted significant radiation over the spectral region to which the

![Figure 3.1: Measured power during the cutting of aluminium](image)

Figure 3.1: Measured power during the cutting of aluminium
detector was sensitive. The background radiation has little significance to hazard assessment. It appears as a non-uniform extended source.

Reflected power was found to be greater for materials with a lower emissivity. Relative changes in reflected power were not found to correlate to the relative changes in emissivity between metals. This was attributed to the complex laser-material interactions occurring during processing. The similarity between reflected powers for mild steel and galvanised steel was because the bulk material was identical in each case, the surface coating played only a small part in the total reflectance.

Neglecting the background contribution, the measured power consisted of scattered 10.6\(\mu\)m radiation and broadband radiation emitted from the laser-workpiece interaction. Both of these sources will appear to originate from a point source and generate divergent radiation. The radiation is predominantly reflected back along the cut, guided by the walls of the cut. This accounts for the greater levels of power measured as the laser cut away from the detector compared to cutting towards the detector. When the cut is not aligned with the centre of the detector lower powers are measured because of the tendency for radiation to be guided by the cut walls.

3.2.1.5 Determination of the radiation hazard

The measurements were made at a distance of 20cm (the closest point the detector could be positioned) from the laser - material interaction. It was found that the power was approximately equal to the MPE in the case of aluminium and stainless steel (assuming that all the measured power originated as reflected laser radiation). As the angle of detector elevation increased the measured power decreased. Only a small zone close to the point of interaction would include radiation levels sufficiently high to exceed the MPE. At practical observation distances the hazard under normal operational conditions would be minimal.

No attempt was made to determine the potential radiation hazard of the broadband emissions from the process zone. Radiation from the process interaction zone is significant from a hazard viewpoint, but should not be assessed as laser radiation. ACGIH TLVs apply to broadband visible and ultraviolet radiation [14] and would have
to be assessed separately from the laser hazard using a spectroradiometer so that the correct hazard weighting factor could be applied to each spectral component. Hietanen et al. [2] investigated the radiation hazards of scattered CO₂ laser radiation and broadband radiation during welding, thermal treatment and cutting of mild steel. It was found that under normal operating conditions the broadband radiation presented a greater hazard than the scattered laser radiation.

The study of the laser processing system demonstrated that the hazard associated with radiation scattered from the workpieces was minimal under normal operating conditions and normal viewing distances. Cutting of aluminium and stainless steel presented the greatest radiation hazard, negligible hazard was associated with the most common operation; cutting mild steel.

3.2.1.6 Limitations of the detectors

The limitations of the instrument which were encountered during the radiation hazard assessment of the CO₂ laser are summarised below. These limitations are not unique to the LM10 detector head, rather they are representative of the limitations encountered using any of the detectors commonly applied to the hazard assessment of CO₂ material processing lasers.

- Measurements using the LM10 head were limited to average power, resolution of individual pulses or transient events was not possible.
- The aperture of the LM10 detector (19mm) was too large. If an aperture had been fitted the sensitivity of the detector would have been too low to provide accurate MPE measurements, even at 10.6μm.
- The LM10 head has no spectral discrimination. It was not possible to separate the contributions of scattered laser radiation and broadband radiation during the assessment of the CO₂ laser system.
- The LM10 head did not discriminate between constant radiation and pulsed laser radiation. Discrimination of pulsed and c.w. radiation would enable the relative contributions of thermal background and scattered laser radiation during material processing to be estimated by operating the laser in pulsed mode.
The power used during the assessment of the CO₂ laser was recorded from the display on the laser console. It was not possible to verify the accuracy of this reading. Measurement of laser beam powers of 1800W is feasible using thermal detectors but water cooling is required to maintain a constant reference temperature and to dissipate the absorbed energy. This is inconvenient for field use. An accurate method of measuring the laser beam power would permit reliable intercomparison between laser installations and processing conditions.
3.2.2 Display laser systems

3.2.2.1 Background details

Visible lasers are frequently used for entertainment purposes during music concerts, outdoor festivals and in night-clubs. Multi-line lasers (mixed Argon Krypton ion) are used to provide blue, green, yellow and red light with total output powers in the range 1 - 10W. The laser output beam is multiplexed to one of a range of effects. These may include scanners for generating line drawings and other scanned effects, filters for colour selection, diffraction gratings and other beam scattering components. Laser generation is usually limited to a single location. Optical fibres are used to distribute laser radiation to effects located around the venue. Mirrors and diffraction gratings may be located around the venue to provide more complex display patterns. The laser beam powers used do not present a hazard to skin, but ocular exposure would cause retinal damage. A computer or dedicated controller may be used to generate the sequence of patterns and effects comprising a show. It is usual to have the control unit separated from the laser.

Guidelines for the control of radiation hazard in laser displays are provided by PM19 [5] and IEC825-3 [6]. These documents described in Appendix 6 (Section 11.6.3.2). The fundamental requirement is that the ocular MPE should not be exceeded during normal operation, or under reasonably foreseeable fault conditions. The exposure duration over which the MPE must be determined varies and is most restrictive for spectators where the MPE should not be exceeded over the duration of a show.

To fully characterise the radiation hazards of a display laser requires measurements of c.w. and pulsed laser radiation. Pulsed measurements are appropriate when a c.w. beam is scanned to generate an effect. As the beam passes repeatedly over the measurement aperture a pulse train is generated. For the purposes of hazard assessment it is immaterial whether the radiation originates from a pulsed laser or scanned c.w. laser. Measurement of c.w. radiation is required for static effects, for example when the laser is reflected from a diffraction grating. During a radiation hazard survey of a display system it is only necessary to consider the radiation which may enter the spectator, ancillary personnel or performer zones. In outdoor events
laser radiation may be excluded from these zones by scanning into the sky, above the audience or onto screens. Indoors it is more usual to direct laser radiation into one or more of the zones.

The need for measurements on pulsed and c.w. radiation meant that a thermal detector alone was unsuitable. It was found that the only detector commonly used for pulsed laser energy measurements was a Coherent LM-P10 or similar detector. The specifications of this head showed that this was not a suitable solution to the pulsed measurement requirements because the maximum pulse repetition rate was only 10Hz and the maximum pulse width 2.3ms. These were too restrictive for the purposes of hazard analysis on the scanned lasers. To enable detailed data regarding the scanning system operation to be obtained an apertured photodiode was constructed. The output of the photodiode was amplified and recorded using a storage oscilloscope, data was then downloaded to a PC for storage. The lower MPE at visible wavelengths (25.4 Wm\(^2\) for a 0.25s exposure) meant that the LM10 head was not suitable for any MPE measurements. A thermal detector head capable of measuring lower powers was constructed to replace the LM10 where average, spectrally independent power measurements were required. This used a thin film thermopile (Dexter 2MC) and digital readout calibrated in microwatts. The thermopile was 2mm square and from this known area the incident irradiance could be calculated.

3.2.2.2 Theoretical considerations

Measurement of the c.w. radiation from static effects is straightforward, requiring only multiple measurements through a 7mm diameter aperture to determine the worst case. Dynamic displays generate a pulse train as the laser beam scans over the detector aperture. It is therefore necessary to verify that the MPE is not exceeded under single pulse, average exposure or reduced single pulse conditions (Section 2.2.4).

During assessments of laser display a common misconception was encountered amongst laser operators. It was assumed that scanning the pattern at increased rates reduced the radiation hazard. The justification given for this is that the pulse width as the laser passes over the pupil is reduced as the scan speed increases. Such a simplistic assessment disregards the fact that increasing the scan rate also increases the repetition
rate at which the eye is exposed. An increase in scan rate therefore makes the reduced single pulse MPE more restrictive. It may be shown that the decrease in hazard arising from the reduction in pulse width is exactly compensated by the increase in hazard arising from the increased pulse repetition rate. This is an inevitable consequence of the fact that "The total energy (damage) threshold for a train of pulses increases as the total on time (exposure) raised to the power of 3/4" [1].

For all pulses longer than 18µs it is therefore impossible to reduce the hazard of a scanned laser beam by increasing the scan rate. Only if the scan rate can be increased to such a speed that the pulse duration becomes shorter than 18µs will the hazard start to reduce. For pulses shorter than 18µs the MPE then varies as t⁻¹ with scan rate.

Increasing distance from the source decreases the radiation hazard. Moving further away from the laser increases the scan velocity without affecting the scan rate. Pulse width therefore decreases with distance from the source. A decrease in the pulse width at a constant repetition rate reduces the pulse energy and average power measured over an aperture and reduces the hazard. The increase in beam diameter caused by the beam divergence will also reduce the average power and pulse energy measured over an aperture by reducing the beam irradiance and radiant exposure.

The radiation hazard will usually vary along the scanned pattern. This is a consequence of the varying scan velocity. Circular Lissajous figures are the exception to the rule, but any more complex pattern will have sections where the scanned beam is accelerating, decelerating or has constant velocity. This is a result of the mechanical inertia of the scanning components. Regions of the pattern where the scan velocity is lowest correspond to the greatest hazard because the width of individual pulses increases whilst the repetition rate remains constant.

In some cases with unsophisticated scanner drivers "hotspots" become visible at low scan rates. Figure 3.2 shows an example of this effect. When the pattern is formed from a series of discrete steps, hotspots occur at the points where the beam halts between steps. As the scan rate is increased the hotspots disappear, this may give support to the belief that increasing the scan rate always reduces the hazard. Hotspots appear brighter because of the greater pulse width. Persistence of vision means that
Figure 3.2: Linear scan of a laser beam in a nightclub showing "hotspots"

the eye responds to the average power, hence the points with the greatest pulse width appear brightest. At increased scan rates the beam does not have time to pause between steps and the hotspots disappear. Increasing the scan rate is therefore only effective at reducing the radiation hazard where hotspots exist. This does not affect the fact that increasing scan rate does not generally reduce the hazard. Hotspots may be regarded as a form of "excess hazard" caused by limitations of certain scanning techniques. A scanning system which did not rely on pausing the beam motion between steps to slow down the scan rate would be free from the excess hazard of hotspots.
3.2.2.3 Laboratory based investigation of a display laser system

A measurement was performed under laboratory conditions using a computer controlled laser scanning system and a low power Argon Ion laser as the radiation source. Hotspot formation was avoided by operating the scanner at a sufficiently high rate. A flat scan was generated by collapsing a circular scan to lie in the y axis only. A pattern such as this would be used to generate the appearance of a solid sheet of light when projected through smoke. As such it also represents a basic component from which more complex effects would be constructed. It is useful to consider the hazard of this simple pattern as a basis from which the hazard of more complex shows could be estimated. A flat scan is also relevant to hazard assessment because it represents the behaviour of a display laser system under the foreseeable single fault condition of a partial scan failure. The pattern would then collapse to a flat scan regardless of the complexity of the intended display.

Figure 3.3 shows the basic form of the displayed pattern. Each section of the scan has been separated to improve clarity, in reality these overlapped to form a single line. Before collapsing the scan into a single line it was examined as a circle. Under these conditions a portion of the circumference appeared brighter than the rest. Investigation of this bright section using the photodiode and oscilloscope showed that it corresponded to a double scanned section. Rather than scanning from an origin around the circle and directly back to the origin the scan overshot. There was then a flyback period during which the beam was blanked. A section of the circle was therefore scanned twice per complete cycle. This feature was inherent in the PC software and could not be removed by user intervention. Collapsing the complex circle to a vertical line introduced anomalies to the results which would not exist had the circle been a single continuous scan.

Marked on Figure 3.3 are illustrative oscilloscope traces at significant parts of the scan. At each extreme erid one long pulse was measured per cycle, this was the point that the beam velocity reached zero before reversing. Moving down from the top the single pulse separated into two shorter pulses. As distance from the top increased the time between pulses increased, but the time for a complete cycle remained unchanged.
Figure 3.3: Idealised diagram of the flat scan showing the overscanned region and typical oscilloscope traces.

For a "normal" scan the time between pulses would reach the maximum halfway along the scan and would equal half the cycle time.

In the case of the scan studied the time between pulses continued to increase almost until the point where the scan overshot. In this region three pulses were apparent per cycle (cycle time remained constant). One originated from the downwards path of the beam, followed soon after by the beam returning from the bottom point. There was then a gap during which time the beam overshot, was blanked, flew back and began the scan again. The final pulse of the three was the beam starting a new scan. The delay between the first and last pulses of the three was longer than between the first two and was relatively unaffected by the position in the triple scan region. Moving further down the scan pattern out of the triple scan region gave only two pulses. The pulse
width was recorded at various locations along the scan. This increased significantly at each end with a rapid decrease to a near constant value over the majority of the scan length. Changes in pulse width are a consequence of the deceleration of the beam as it approaches the end of the scan and the rapid acceleration to near constant velocity for the remainder of the scan. Where three pulses were present per cycle, the lengths of the longest two (the first) were recorded. These represented the true scanned behaviour of the beam. It appeared that the final, third pulse originating from the start of a new scan after flyback was of shorter duration, implying that the beam had accelerated before blanking was removed. Figure 3.4 shows the variation in pulse width over the length of the scan illustrated in Figure 3.3. Figure 3.5 shows the change of time between pulses over the same scan length. The time per cycle remained constant over all measurements.

The change of time between pulses does not affect the radiation hazard, as discussed in Section 2.2.4 the biological damage threshold is determined by the total on time of the pulse train, implying the mode of delivery to be unimportant. On the same basis the merging of two pulses per cycle into one at the scan ends does not increase the hazard because at the same time the repetition rate halves. However, the change in pulse width along the scan does affect the radiation hazard. An increase in pulse width for a constant repetition rate increases the hazard. Radiation hazard is concentrated at the scan ends where the pulse width increases. Over the majority of the scan length pulse width is near constant so the hazard is also near constant. This makes the end points of the scan more hazardous; the repetition rate decreases by a factor of two, but as Figure 3.4 shows, the pulse width increases by a factor of ten.

In the particular pattern investigated the hazard was greater towards the bottom of the scan where three pulses were present per cycle. This increased the total on time for the pulse train. More detailed measurement of the pulse widths or total energy would be necessary to determine whether the greatest hazard existed at the very end of the scan, or in the triple scanned region.
3.2.2.4 Investigation of a nightclub laser display system

To support the laboratory based measurements the radiation hazard of a display laser system installed in a nightclub was assessed. The system generated a range of scanned effects and diffraction grating effects, some of which were intentionally projected into the spectator zone. A multi-line (argon krypton) laser generating a "white" beam was used. Individual colours were selected using filters, or by separating the beam into individual laser lines using diffraction gratings. Figure 3.6 shows the plan of the venue and the beam lines of one of the effects.

Two effects typify the most significant radiation hazards encountered during the assessment. The first was a linear scan of the main beam on to the dance floor, the second a diffraction grating effect with diffracted orders incident on the dance floor. Assessing a linear scan was a simplification of the more complex patterns which were routinely used, but as explained for the laboratory tests is useful for hazard analysis.

Figure 3.6 shows the details of the measurement positions. Figure 3.2 shows the venue and the linear scan of the main beam on the dance floor. Measurements were made at three points along the scan, at maximum and minimum scan rate using the photodiode and oscilloscope. The beam diameter was measured as approximately
Figure 3.6: Plan of the nightclub showing the measurement locations
30mm, affected by the subjectivity of visually estimating beam diameter. Beam diameter increased negligibly between the three measurement locations.

Table 3.2 contains the pulse widths measured from the oscilloscope traces. At all scan rates and measurement positions a train of rectangular pulses was observed. This was because the pulse power was constant and determined by the beam irradiance. It was calculated that the pulse amplitude corresponded to a pulse photocurrent of 90mA. This was greater than the manufacturer's recommended maximum continuous forward current (10mA) but less than the maximum pulse current (200mA for 1μs) [88]. No degradation in performance was observed. It was not possible to determine an exact responsivity figure for the photodiode because of the multi-line laser output. From the manufacturer's data [88] a value of 0.35 was estimated. The pulse power measured through the 7mm diameter aperture was therefore 0.26W, corresponding to an irradiance of 6682Wm⁻².

<table>
<thead>
<tr>
<th>Measurement position (see Figure 3.6)</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pulse width</td>
<td>MPE</td>
<td>Pulse width</td>
</tr>
<tr>
<td>223Hz scan rate, maximum amplitude</td>
<td>350μs</td>
<td>2.7Wm²</td>
<td>75μs</td>
</tr>
<tr>
<td>223Hz scan rate, minimum amplitude</td>
<td>400μs</td>
<td>2.6Wm²</td>
<td>88μs</td>
</tr>
<tr>
<td>22Hz scan rate, minimum amplitude</td>
<td>4.2ms</td>
<td>2.6Wm²</td>
<td>900μs</td>
</tr>
</tbody>
</table>

Table 3.2: Pulse widths measured along flat scan and associated MPEs.

At the low pulse repetition rates encountered in the measurements and for an exposure limited by the blink reflex (0.25s) the reduced single pulse MPE applies. This has been calculated for each repetition rate and pulse width in Table 3.2. The reduced single pulse MPEs have been expressed in terms of irradiance because the pulse power remained constant for all measurements. It is apparent that the original design of the light show would allow hazardous laser radiation to be incident in the spectator zone.
It is also apparent that the increase in scan rate does not affect the reduced single pulse MPE value, the hazard exists equally at maximum and minimum scan rates.

The laser beam lines forming part of the diffraction grating effect assessed are shown in Figure 3.6. Four laser beams (multi-line) were emitted from the main laser unit. Two were directly incident on reflective diffraction gratings, the other two were reflected from mirrors onto reflective diffraction gratings. The diffraction gratings divided the incident beam into individual spectral lines and directed the diffracted orders down towards the dancefloor. In each case the laser beam power incident on the grating and that of the first diffracted order was measured using the LM10 head. The MPE for a 0.25s exposure was exceeded in each case. This technically represented a hazard since the height of the beams was less than 3m above the dancefloor (as required by PM19 and IEC825-3). Of greater concern were the diffracted orders since they were directed into the audience. The power of these diffracted beams was measured using the low power thermopile detector. It was found that the red (647.1nm) component of the pattern gave the highest irradiance. Table 3.3 summarises the measurements made on one of the diffraction gratings. Again it was found that potentially hazardous irradiances were being directed into the spectator zone.

<table>
<thead>
<tr>
<th>Measurement location (see Figure 3.6)</th>
<th>Measured power (W)</th>
<th>Calculated irradiance (Wm^-2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incident beam.</td>
<td>0.7</td>
<td>2465</td>
</tr>
<tr>
<td>Fundamental of diffracted pattern.</td>
<td>0.03</td>
<td>106</td>
</tr>
<tr>
<td>Maximum of diffracted pattern on dancefloor.</td>
<td>$330 \times 10^{-6}$</td>
<td>82.5</td>
</tr>
</tbody>
</table>

Table 3.3 : Summary of measurements made on diffraction grating effect.

The laboratory and field studies of the radiation safety of display laser systems had benefits beyond the original intention of investigating instrumentation requirements. It was shown by measurement and calculation that commonly held beliefs within the industry that audience scanning was safe and that an increased scan rate reduced any hazard were false. Following these findings, research was continued by the National Radiological Protection Board in the UK into the hazards associated with display
lasers. The fact that existing and proposed guidelines are being ignored strengthens the case for development of improved instrumentation for MPE assessment. A combination of unsuitable equipment and lack of understanding of laser hazard assessment is preventing Environmental Health Officers from fully performing their duties relating to the task of laser hazard assessment.

3.2.2.5 Limitations of the detectors

It was apparent at the start of the work that on the occasions that laser display operators did perform radiation hazard assessments that the instrumentation was inappropriate. Simple detectors were constructed in order that useful measurement data could be obtained. Limitations encountered during the work are summarised below:

- Assessment of the display laser systems required detectors capable of resolving a wide range of pulse widths and repetition rates. Pulse widths ranged from tens of microseconds through to c.w. exposure whilst repetition rates ranged from c.w. to several kilohertz. It was found that the LM-P10 detector was unsuited to the measurement requirements. A serious problem was encountered during the investigation. The LM-P10 responded to pulse trains up to 20Hz but provided erroneous readings. There was no indication that the instrument was operating beyond the specified range, or that the results were in error.

- The suitability of the LM2 detector head for making pulsed measurements was investigated. This is a silicon detector and in theory would be capable of pulse resolution. It is specified only for c.w. operation when used with the Labmaster and Fieldmaster, but a peak detection function is available which was thought could be of use for hazard assessment. A high intensity LED was used to generate a pulsed optical signal. It was found that single pulses with duration less than 60ms caused unreliable operation, those shorter than 20ms generated no response. This feature is therefore of limited use for hazard assessment.

- The oscilloscope and photodiode combination used for the assessment of scanned laser displays was complex to use. A non expert user would be unable to interpret the results.
Calculation of MPEs and comparison to the measured power or energy was a manual process. Reports of other problems associated with user error and a lack of understanding of instrumentation performance were encountered during the investigation. An extreme example which was encountered in a display laser situation was the use of a meter and head intended for measuring intrabeam laser power (3-4W) to verify that levels of radiation scattered into the audience did not exceed the MPE. This head had 1mW resolution and would be of little use for determining whether the MPE had been exceeded (the MPE being $980 \mu W$ over a 7mm diameter aperture for a 0.25s exposure). A more serious problem was that when used to assess a scanned beam the reading appeared to be zero and it was falsely assumed that there was no hazard. In fact the beam had a peak power sufficient to exceed the single pulse MPE, but a low average value. Exposure would therefore be hazardous, but by using inappropriate instrumentation this hazard was unknowingly overlooked.

Another user problem reported was when a low power silicon photodiode detector was used with the removable attenuator left in place. Consequently readings on the meter were a factor of one hundred too low. In that case the operator realised that the results were in error, but a less experienced operator could well have accepted the erroneous results and vastly underestimated the hazard potential.
3.3 INSTRUMENT SPECIFICATIONS

Specifications for application specific instrument are based on the analysis of the measurement requirements from the laser radiation safety standard (Section 2.2), the limitations identified in using commercially available instrumentation (Section 2.3.3) and the practical considerations identified during the case studies described in this chapter.

The fundamental design decision was to adopt a modular structure for the instrument. This was essential in view of the need to use several detector types to obtain the necessary spectral response, but brought additional advantages.

- Initial signal processing may be performed in the detector head. Low amplitude detector outputs may be amplified for transmission to the meter thereby reducing the risk of electromagnetic interference (EMI) to the signal.
- The display is separated from the measurement point and by implication from the laser radiation. It would be bad safety practise to require the user to have their eyes in proximity to the measurement position to read the results.
- Duplication of circuitry may be minimised by configuring each detector head to provide a standard electrical signal output regardless of the detector type. Avoiding duplication reduces the cost of the complete instrument.
- Putting only the essential signal processing electronics in the detector head enables the head to be made small. This is important if the area permitting access to the laser radiation is small and for hand held applications.
- The principle aim of the work was to address the problems of laser radiation hazard assessments. Investigation of the wider aspects of laser safety was not ruled out. Utilising a modular design approach helped to ensure that the final instrument design remained adaptable to new tasks.
- A modular implementation reduces the risk of instrument obsolescence. A particular problem could be changes in the MPE values contained in the standard [3]. Implementing the task specific functions in software can reduce the impact of such changes if the measurement hardware is made generic in function.
The need for robust detectors was highlighted during the display laser assessment, the measurements on the flat scan involved irradiances considerably above the MPE. Under such conditions it is important that the detector is not damaged. Even if the detector saturates the output should not decrease below the maximum value at high irradiances to prevent a high power being mistaken for a much lower one. If equipment is to be used by unskilled personnel it is quite possible that the detector could be exposed to damaging levels of radiation.

The specifications for the instrument based on the work of Chapters 2 and 3 are summarised below:

**User requirements:**
- Cross checking of entered data.
- Text display with guidelines on human computer interfacing to be applied.
- Numerical and relative display of results.
- Individual coding of the elements of the instrument.
- Elements to be cross checked against data entered by user.

**Spectral region:**
- 180nm to 10.6μm. Emphasis to be placed on visible, Nd:YAG and CO₂ lasers because of the predominant commercial use of such lasers.

**Detector types:**
- Photodiodes for UV, visible and near infrared, thermopile and pyroelectric detector between 1.5μm and 10.6μm.

**Continuous wave measurements:**
- Measurement of average and maximum irradiance over a measurement period. This may be achieved by a measurement of the total radiant exposure and maximum irradiance over the measurement duration.

**Pulsed measurements:**
- Measurement of total radiation present time, total radiant exposure, maximum irradiance over a measurement period and number of pulses (also see next item).
- Automatic detection of c.w. and pulsed inputs.
- Discrimination of pulsed and (background) c.w. radiation at 10.6μm.

**Pulse width and repetition rate:**
- Maximum pulse repetition rate at which individual pulses to be distinguished and counted 56kHz.
- Minimum pulse width to be measured 18μs (excluding certain ultraviolet and infrared wavelengths at which pulse
width is only required for the MPE calculation).
Maximum pulse irradiance to be measured for pulses longer than 18μs, maximum pulse radiant exposure for pulses shorter than 18μs (longer pulse widths for changeover apply at certain spectral regions.)

Extended source measurements:
Use detectors with field of view sufficient to ensure that all of the radiation from an extended source is included in the measurement. Treat extended source as a point source.

Miscellaneous:
Control background radiation using spectrally selective detectors, minimising the field of view (subject to requirements of extended source measurement) and implementing a background subtraction function.
Instrument accuracy to exceed Class 10 to BS EN 61040.
Measurement distance 10cm.
A means of detecting and warning of detector overload and possible damage is required.
Temperature effects to be compensated over the range 0°C to 40°C.
3.4 SUMMARY

Two laser applications in which radiation measurements were useful as part of a hazard assessment were investigated. The suitability of general purpose, commercially available laser radiation measurement equipment for the purposes of laser radiation hazard assessment was considered. Instruments used were selected to be representative of the types known to be used for hazard assessment and were not necessarily optimum for the task. Various practical limitations in the commercially available instrumentation were encountered during the case studies. These limitations furthered the case for development of application specific instrumentation. The measurement examples highlighted the fact that practical radiometry for laser radiation hazard assessments is not straightforward. Selection of appropriate measurement equipment is made difficult by the lack of suitable instrumentation. It is important that the limitations of instruments are appreciated. This suggests the need for users to be trained both in instrument selection and instrument use.

It was found that under normal operating conditions the laser radiation hazards of the CO₂ laser machining system were minimal. This was helped by a responsible attitude towards safety on the part of the laser system manufacturers. The system had been designed to prevent human access to hazardous levels of radiation. During the assessment of the display laser system significant laser radiation hazards were found. These originated in an erroneous belief that increased scan rate automatically reduced the radiation hazard. Detailed analysis of a scanned laser system in laboratory and field conditions showed that this was not the case. The hazards were generally not appreciated because on the occasions when measurements for hazard assessment were performed, inappropriate instrumentation was used. The power meters used generally had insufficient sensitivity and were unable to resolve the hazardous energy of short pulses. As a result significant numbers of people in the audience of laser displays were being exposed to hazardous levels of laser radiation.

The results of the analysis of the measurement requirements in the standard, the user requirements and the practical experience were summarised as a set of specifications for the instrument.
4 DESIGN OF THE DETECTOR HEADS

4.1 INTRODUCTION

In Chapters 2 and 3 the specifications for an instrument dedicated to laser radiation hazard assessment were developed. Theoretical analysis of the MPE values in the standard dictated many of the measurement requirements. Pulsed laser radiation measurement has the most complex set of requirements and represents the area where conventional instrumentation is least well suited to laser radiation hazard assessment. It was shown that it is unnecessary to resolve pulses shorter than $18\mu s$ duration or pulses at a repetition rate greater than $56\text{kHz}$ (in the majority of spectral regions). For pulses shorter than $18\mu s$ it is necessary to measure the energy of individual pulses and detect the presence of deviant pulses with greater than average energy. For pulses at repetition rates greater than $56\text{kHz}$ it is necessary to record the total energy over a measurement duration without necessarily resolving individual pulses. If the train contains a deviant pulse with greater energy than average then this has to be detected. For all other pulses it is necessary to record the pulse power and the total energy received over the measurement period. Commercially available instrumentation is not capable of measuring these parameters.

The findings of this analysis are extremely significant for the design of laser radiation hazard assessment equipment. Since it is not necessary to temporally resolve pulses with duration shorter than $18\mu s$ the bandwidth requirements of the electronic circuitry are reduced. This minimises the noise generated by the detector head which facilitates measurement of low power laser sources. Cost of the instrument is also reduced. It is important that the energy of short pulses is measured accurately, and that the instrument can detect short pulses with greater than average energy.

The measurement requirements for pulses longer than $18\mu s$ are addressed using an integrator and peak detector in the interface unit. The integrator provides an output proportional to the energy received during the measurement period and the peak detector an output proportional to the maximum power received during the measurement period. Short pulses are processed in the detector head. A novel design is developed for the measurement of the energy of short pulses and implemented in the
photodiode detector head. The design stretches short pulses whilst conserving energy to provide short term integration. An important advantage of the approach is that for short pulses the maximum output voltage is proportional to the pulse energy.

Photodiodes, a pyroelectric detector and a thin film thermopile detector were selected as a suitable basis for the detector heads. Each detector head required specific signal processing to provide an output in a format suitable for use by the interface unit. This chapter describes the design of each detector head. In each case an electrical model is developed for the detector and practical devices are evaluated. The design of the signal processing electronics is described, including further modelling as required. The gain required in each detector head is calculated using the values of power and energy associated with MPE measurements and the detector responsivity. Finally noise sources are considered.

The chapter concludes with consideration of the optical performance of detector heads. The optical components are important for aspects of the measurement task such as defining the measurement aperture and angle of acceptance.

Laser wavelength is a factor in the assessment of laser radiation hazards. A detector which was capable of determining the laser wavelength is of use for certain spectral regions and would reduce the amount of data to be entered by the user. Various strategies were considered and preliminary investigations performed. Appendix 7 contains details of the work.
4.2 DESIGN OF THE PHOTODIODE DETECTOR HEAD

4.2.1 Introduction

The photodiode detector head is required to measure c.w. and pulsed laser radiation and to implement a pulse stretching, energy conserving function for pulses shorter than 18\mu s.

A silicon photodiode was used in the prototype. Silicon photodiodes are suitable for operation with a variety of common visible and near infrared lasers. The use of a single photodiode type was sufficient to prove the design, it would be straightforward to apply the concepts to alternative devices. The spectral range was restricted to between 400nm and 950nm. For ultraviolet measurements it was necessary to use a detector with an intrinsic insensitivity to longer wavelengths to prevent background radiation swamping the contribution of the ultraviolet radiation. This excluded the use of a silicon photodiode. The long wavelength limit was set at 950nm to restrict operation to the spectral region where responsivity was a monotonic function of wavelength. This simplified the expression required for spectral correction of the photodiode output. An additional advantage of operating over the more limited spectral range was that the sensitivity of responsivity to temperature was reduced.

The design process considered the methods and implementation of pulse stretching, the gain required in the detector head, the noise performance of the proposed design and finally the application of the design to alternative types of photodiode for other spectral regions.

4.2.2 Photodiode electrical modelling

An equivalent circuit for a practical photodiode is shown in Figure 4.1 [46]. The current source $I_p$ models the photo-generated current applied across an ideal diode $D$. $R_{sh}$ is termed the shunt resistance, $R_s$ the series resistance, $C_j$ the junction capacitance and $C_L$ the combination of load and stray capacitance. An ideal photodiode would have infinitely high shunt resistance and zero series resistance.

The series resistance is composed of two components, one is the series resistance at the attachment points for the leads, the second is the bulk resistance of the
Figure 4.1: Electrical model of a photodiode

Semiconductor. Bulk resistance becomes particularly significant if the incident radiation is concentrated in a small spot. Photogenerated carriers are then forced to flow through the bulk semiconductor resistance to the contact. This resistance will vary according to the distance from a contact and will be greater than the effective resistance under uniform illumination.

Series resistance affects the maximum linear photocurrent and response time. Photocurrent generates a voltage across the series combination of $R_s$ and the external load resistance ($R_L$). This voltage tends to forward bias the diode and reduces the current measurable externally. As the voltage across the diode increases, the diode current rises exponentially which makes the increase in external current non-linear. Applying a reverse bias to the diode overcomes the tendency for forward bias and permits higher currents for linear operation. Reverse bias also reduces the magnitude of the bulk resistance [46].

Series resistance affects the response to short pulses by controlling the rate at which external load capacitance ($C_L$) can be charged and the junction capacitance ($C_J$) discharged. This electrical time constant usually dominates the response time [44,46] and may be estimated from:

$$\tau_{\text{electrical}} = (R_s + R_L)(C_J + C_L)$$

Photodiode response time may be estimated from the sum of the component parts:

$$\tau_{\text{response}} = (\tau_{\text{electrical}}^2 + \tau_{\text{charge collection}}^2 + \tau_{\text{diffusion}}^2)^{0.5}$$

98
Charge collection delay is the time taken for photo-generated charge carriers to be removed from the depletion layer. Diffusion time is the time taken for photo-generated carriers outside the depletion layer to diffuse to the depletion layer. This becomes more significant at long wavelengths and in devices where the depletion layer does not extend to the back of the device (whether by design or through lack of reverse bias). Under some conditions the diffusion time may be several microseconds [89].

Finite shunt resistance exists predominantly because of thermally generated minority charge carriers. Consequently shunt resistance decreases with increasing temperature. Shunt resistance is maximised by using material with a minimum number of crystal defects [90]. The high value of shunt resistance makes it unimportant in determining device response time.

A photodiode may be operated in one of two modes [46]. The voltage measured across $R_L$ with $R_L$ comparable to or greater than $R_{sh}$ is proportional to the natural logarithm of the photogenerated current and by implication to the natural logarithm of the incident power. This is termed photovoltaic mode. Linear operation may be obtained by measuring the detector short circuit current using a value of $R_L$ much smaller than $R_{sh}$. Reverse bias may be applied to increase response speed and responsivity. The disadvantage is that reverse bias increases the dark current.

### 4.2.3 Evaluation of practical devices

The photodiodes suitable for the MPE assessment application require a low series resistance so that high pulse powers can be measured accurately, a high shunt resistance to minimise shot noise generation when biased (and the ability to withstand reverse bias) and a long carrier lifetime to minimise recombination. Design effort concentrated on using silicon photodiodes. This enabled the prototype to be tested on a wide range of common laser types. Additional specific detector requirements were a peak of responsivity at or beyond 950nm so that the spectral dependency of responsivity remained monotonic and the ability to resolve pulses down to at least 18μs. A comparison of the parameters for a range of devices from several manufacturers was used to locate the optimum component. There were a number of
possibilities, of these the S2386 and the S1223 from Hamamatsu were the best candidates. It was expected that the high shunt resistance of the S2386 would make it the optimum device. Detailed evaluation revealed disadvantages to this device.

The linear drive board (Appendix 1) with all five LEDs operating was used to investigate the effect of reverse bias on photodiode linearity and response speed. Figure 4.2 shows the response of the S2386-45K device to pulses of red light with 15V reverse bias. Figure 4.3 shows the response under the same operating conditions but using the infrared LEDs. The output took approximately 100\(\mu\)s to reach a steady state value for infrared radiation but showed no such behaviour with red light. Increasing the reverse bias made negligible difference. This response made the device unusable in the intended application because it would prevent the proper resolution of pulses shorter than 100\(\mu\)s. The probable cause of this slow response was the device having only a relatively shallow junction which was not designed to efficiently collect carriers generated beyond the junction region. Reverse bias was not capable of increasing the depletion layer thickness sufficiently to collect these carriers.

For comparison Figures 4.4 and 4.5 show the response of an S1223 device to pulses of red light (note the faster timebase than the S2386 results) with and without reverse bias. Figures 4.6 and 4.7 show the response to infrared light. It is apparent that at both wavelengths the response time decreases when reverse bias is applied. The response to pulses of infrared light was slower than to red light. The photodiode output still reached the steady state value in less than 10\(\mu\)s. This is perfectly adequate because the head design was not attempting to resolve pulses shorter than 18\(\mu\)s.

Responsivity of the S1223 device was found to increase with reverse bias at both red and infrared wavelengths. This is a function of improved charge collection efficiency and reduced recombination as the depletion layer widens. Approximately 2V bias was required to sufficiently deplete the device for red light. Larger bias voltages caused minimal change in rise time or responsivity. This was because increasing the depletion layer thickness beyond the depth required to absorb the majority of photons can cause only marginal changes in device behaviour. Infrared radiation required greater reverse bias voltages to maximise the responsivity. Table 4.1 summarises the effect of
Figure 4.2: Output current of 52386 photodiode for pulses of red light with 15V reverse bias. CH1 (Optical input) 0.1V/div, CH2 (photodiode output) 20mV/div. X 50μs/div.

Figure 4.3: Output current of 52386 photodiode for pulses of infrared light with 15V reverse bias. CH1 (Optical input) 50mV/div, CH2 (photodiode output) 20mV/div. X 50μs/div.

Figure 4.4: Output current of 51223 photodiode for pulses of red light with 15V reverse bias. CH1 (Optical input) 0.5V/div, CH2 (photodiode output) 50mV/div, X 20μs/div.

Figure 4.5: Output current of 51223 photodiode for pulses of red light with 0V reverse bias. CH1 (Optical input) 0.5V/div, CH2 (photodiode output) 50mV/div, X 20μs/div.

Figure 4.6: Output current of 51223 photodiode for pulses of infrared light with 15V reverse bias. CH1 (Optical input) 0.1V/div, CH2 (photodiode output) 0.1V/div, X 20μs/div.

Figure 4.7: Output current of 51223 photodiode for pulses of infrared light with 0V reverse bias. CH1 (Optical input) 0.5V/div, CH2 (photodiode output) 0.1V/div, X 20μs/div.
different reverse bias voltages on the S1223 photodiode output to pulses of infrared radiation. The units of response are arbitrary and based on the peak to peak display of the photodiode output on the oscilloscope. A pulse width of 60μs was used to ensure that the photodiode output reached a steady state value.

The response almost saturated in the first few volts of bias. This behaviour was as expected from the work of Edwards and Jefferies [89], it is a consequence of the long carrier lifetime associated with the very pure silicon used in photodiodes. Carriers formed outside the depletion layer have a high probability of reaching the depletion layer without recombining even at the low velocities caused by the field strengths associated with low bias. On the basis of these results it is apparent that a reverse bias of 15V provides sufficiently close to the maximum responsivity and that minor fluctuations around 15V bias will introduce negligible changes in responsivity.

<table>
<thead>
<tr>
<th>Response (arbitrary units)</th>
<th>Response (percentage of maximum)</th>
<th>Bias voltage / V</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.0</td>
<td>80%</td>
<td>0</td>
</tr>
<tr>
<td>6.8</td>
<td>90.7%</td>
<td>1</td>
</tr>
<tr>
<td>7.1</td>
<td>94.7%</td>
<td>5</td>
</tr>
<tr>
<td>7.3</td>
<td>97.3%</td>
<td>10</td>
</tr>
<tr>
<td>7.4</td>
<td>98.7%</td>
<td>15</td>
</tr>
<tr>
<td>7.4</td>
<td>98.7%</td>
<td>20</td>
</tr>
<tr>
<td>7.5</td>
<td>100%</td>
<td>25</td>
</tr>
<tr>
<td>7.5</td>
<td>100%</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 4.1: Effect of reverse bias on responsivity of S1223 photodiode to 60μs pulses of 950nm radiation.

To investigate the linearity of the photodiodes a function generator was used to apply a triangular waveform to the linear LED drive board. Photodiode non-linearity was evident as a flattening of the peak output when the function generator signal and photodiode output waveforms were superimposed on the oscilloscope. A range of load resistances between 100Ω and 100kΩ were used in conjunction with reverse bias between 0V and 15V. Significant non-linearity of photodiode output was observed when the voltage across the load resistor exceeded the reverse bias voltage + 0.2V for infrared light and the reverse bias voltage + 0.3V for red light. Maximum linear
photocurrent was therefore found to be a function of the load resistance and reverse bias as expected from the device model described in Section 4.2.2. The use of reverse bias and a transimpedance amplifier (which will approximate to a zero ohm load) provides for linear operation over a wide range of photocurrents.

Photodiodes have good spatial uniformity, variations typically are less than 0.5% over the surface [91,92]. This was verified for a S2386 device using the method described in Appendix 4.

4.2.4 Design of the pulse stretching circuit

The pulse stretching function was implemented using a passive network. This avoided the need to use wide bandwidth active electronics. Resistor - Capacitor (RC) and Inductor-Capacitor-Resistor (LCR) implementations were considered. In each case the capacitor is connected in close proximity to the photodiode and is a low inductance type (such as multilayer ceramic). The photogenerated charge from short pulses is stored on the capacitor. For the RC circuit a resistor connects to the inverting input of an operational amplifier based transimpedance amplifier. This input represents a virtual earth, the capacitor therefore discharges with a time constant equal to the RC product and increases the fall time of a short pulse. The rise time is limited only by the speed of the transimpedance amplifier which is dependent on the amplifier gain. Such a situation is undesirable since it means the bandwidth requirement of subsequent electronics is not accurately defined. A means of controlling both rise and fall time of the detector head output independently of the amplifier characteristics is required. In the LCR circuit an inductor and resistor are connected in series to the transimpedance amplifier input. The period of the LCR circuit determines the temporal characteristics of the output signal and modifies the rising and falling edges of the input pulse.

Figure 4.8 shows the fundamental components of the photodiode based detector head using an LCR circuit to perform pulse stretching. To understand the response of the circuit to short pulses it is best regarded as consisting of three sections; a slightly overdamped tuned circuit, a transimpedance amplifier and a voltage amplifier. Photo-generated current from the photodiode is injected into the capacitor of the tuned circuit. The input to the transimpedance amplifier is a virtual ground for frequencies
TRANSIMPEDANCE AMPLIFIER

DAMPED TUNED CIRCUIT

VOLTAGE AMPLIFIER

C L R

OUTPUT

Figure 4.8: Simplified diagram of the pulse stretching photodiode head

which do not exceed the gain bandwidth or slew rate limitations of the operational amplifier. Charge on the storage capacitor arising from the photocurrent is removed at a rate determined by the period of the tuned circuit. The series resistor damps the tuned circuit sufficiently that the output is a single cycle with minimal overshoot. The charge in this cycle is equal to that injected from the photodiode.

Using a tuned circuit to define the output pulse width means that the maximum output voltage when the optical pulse width is much shorter than the period of the tuned circuit is proportional to pulse energy. This provides a simple and convenient means of measuring pulse energy for the pulse widths where energy determines the hazard. It is possible to detect individual pulses having greater than average energy by comparing the maximum and average detector head output voltages. The detector head design is therefore well matched to the specific task of laser radiation hazard assessment and by reducing the electronic bandwidth required has the advantage of reducing noise.

For pulses much longer than the period of the tuned circuit there is negligible effect on the pulse profile. The resistor damping the tuned circuit degrades the virtual earth that the transimpedance amplifier would otherwise provide for the photodiode. Photocurrent flowing through the resistor to the virtual earth causes a steady state voltage to be impressed on the photodiode. A low value of resistor ensures that this voltage remains insignificant when compared to the photodiode bias voltage. An
additional function of the series resistor is to limit the photocurrent during optical overload conditions (see Section 2.4.2.4 for comments regarding photodiode damage).

In the frequency domain the effect of the pulse-stretching network is to roll off the transimpedance at 20dB per decade above the resonant frequency of the tuned circuit. It therefore reduces the bandwidth available for photocurrent amplification which would be obtained from a basic transimpedance amplifier.

The photodiode detector was operated with reverse bias. This provides faster response and more efficient collection of photogenerated charge carriers than unbiased or photovoltaic operation. A photodiode reverse bias of 15V was used. This was available as the operational amplifier supply and avoided the need for an additional bias voltage. On the basis of the photodiode investigation (Section 4.2.3) it was apparent that a reverse bias of 15V was sufficient to give near optimum charge collection. Variations of 10% in the bias would have negligible effect on the responsivity for wavelengths shorter than 950nm. The maximum photocurrent generated by a short pulse of radiation corresponding to the MPE was defined as 20mA. This ensured that the manufacturer’s specifications [92] were not exceeded.

Three factors control the component selection for the LCR filter:

1. The capacitance must be large enough to ensure that for short pulses (assumed to be quarter of an LCR period) when little charge is extracted by the amplifier the voltage across it is less than 1.5V. For long pulses (>18μs) the value of R must likewise be sufficiently low that the maximum photocurrent causes less than 1.5V drop. This ensures minimal changes in responsivity caused by changes in the effective bias voltage.

2. In combination with the inductor, the value of R should make the circuit critically, or slightly over-damped (0.5<quality factor<0.707) to ensure a single pulse with minimal overshoot is generated.

3. In the prototype it was necessary that pulses with width greater than 18μs were resolved. For shorter pulses only the pulse energy was significant. A measure of individual pulse energy was required for all pulse repetition rates less than
56kHz. The period of the LC circuit was set at 14\(\mu\)s, this being the undamped period for a full cycle. In this application with critical damping the period for a single unipolar output pulse is marginally longer than the undamped period.

On the basis of these criteria, suitable component values can be determined. Applying a 20mA 3.5\(\mu\)s pulse corresponds to a charge of 70nC. For a maximum capacitor voltage of 1.5V a capacitance of 47nF is required. An inductance of 100\(\mu\)H provides the required period. A tuned circuit consisting of 100\(\mu\)H and 47nF has natural frequency \(\omega_0 = 461 \times 10^3\) rad/s. To achieve a quality factor of between 0.5 and 0.707 requires a series resistance between 65\(\Omega\) and 92\(\Omega\) (quality factor = \(\omega_0 \times L / R\)). The other limit for the series resistance is for the voltage drop at maximum photocurrent (20mA) to be less than 1.5V. This dictates a resistance less than 75\(\Omega\). A 68\(\Omega\) resistor was used in the prototype.

The design of the inductor is important. To reduce the risk of interference from external magnetic fields the windings should be within a closed magnetic path. The ferrite should retain a low loss at high frequencies. A toroidal core (Philips 432202097180, 4C65 ferrite) was used in the prototype.

An additional voltage amplifier was required since the single operational amplifier used for the transimpedance amplifier could not provide sufficient gain and bandwidth.

4.2.5 PSpice simulation of the pulse stretching head

The operation of the photodiode detector head was investigated in detail using PSpice simulation of the circuit. Using the simulated detector head it was possible to verify the design calculations and closely observe the operation of the circuit. This provided rapid proof of the concept.

It was found that for long (>20\(\mu\)s) pulses the only effect of the pulse stretching network was to increase the rise and fall times of a pulse. The pulse width measured at half maximum pulse amplitude was unchanged. The maximum output voltage was proportional to the pulse input current. For short pulses (<20\(\mu\)s) the detector head output was a single damped sinusoidal pulse with minimal overshoot. The pulse width
at 50% points was approximately 7μs. It was confirmed that the maximum output voltage was proportional to the input charge.

To verify the function of the pulse stretching head, pulses with constant charge but varying widths were injected into the simulated circuit and the maximum output voltage recorded. The transimpedance stage had a gain of 200, the voltage amplifier stage a gain of unity. Figure 4.9 shows the results. The two operating modes of the head are apparent. For short (<2μs) pulses the maximum output voltage was constant and proportional to pulse energy. Pulses longer than 10μs generated a maximum output which was proportional to the pulse power. In the intermediate region there was no simple relationship.

![Figure 4.9: Simulated effect of input pulse width on pulse stretching head output for constant pulse energy.](image)

The response of the detector head to pulses of constant charge (5nC) but differing modes of delivery was investigated. Again a transimpedance gain of 200 and voltage amplification of unity were used. It was observed that the maximum output voltage remained constant, demonstrating that the maximum output voltage was proportional to the pulse charge (energy). Table 4.2 summarises these results.

107
### Pulse details

<table>
<thead>
<tr>
<th>Pulse details</th>
<th>Maximum output voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>10ps rise and fall, 50ns on</td>
<td>227.4mV</td>
</tr>
<tr>
<td>10ns rise and fall, 40ns on</td>
<td>227.8mV</td>
</tr>
<tr>
<td>20ns rise and fall, 30ns on</td>
<td>227.7mV</td>
</tr>
<tr>
<td>40ns rise and fall, 10ns on</td>
<td>228.5mV</td>
</tr>
<tr>
<td>50ns rise and fall, 10ps on</td>
<td>227.5mV</td>
</tr>
</tbody>
</table>

Two pulses, 50ns duration each. 227.6mV

Single pulse, first part 20ns duration with tail to 400ns. 223.7mW (total input charge lower than previous cases)

### Table 4.2: Simulated silicon photodiode head maximum output voltage for various constant charge inputs.

#### 4.2.6 Calculation of the gain required in the detector head

The values of gain required from the photodiode head were determined from the interaction of the incident powers corresponding to the MPE and the wavelength dependent photodiode responsivity. It was necessary that the detector head output remained in the voltage range 20mV to 4V. The upper limit is defined by the full scale of the ADC, the lower by the resolution of the ADC (1mV) and the need to avoid the effects of noise. Where possible the output voltage was preferred to be in the range 200mV to 4V; a 20:1 variation. Maximum photocurrent is generated by short pulses at the long wavelength limit of operation (950nm). Both MPE and responsivity are at a maximum at 950nm. The minimum photocurrent corresponds to a 30 000s exposure at 400nm. Both MPE and responsivity are at a minimum under these conditions. Table 4.3 shows the relevant information for the calculation of photocurrent.

The 18μs pulse width adopted to define the minimum pulse width at 950nm does not correspond to the minimum which could be encountered. It represents the shortest pulse width before the photocurrent could exceed the maximum specified by the manufacturer. For shorter pulses some form of optical attenuator would be required to
ensure that the photodiode was not damaged by either the high pulse power or photocurrent associated with short pulses. This choice of pulse width as a minimum for the determination of gain is also appropriate because it corresponds to the point at which the pulse stretching function becomes operative. Stretching shorter pulses ultimately generates a maximum output amplitude proportional to pulse energy. Since the MPE is a constant energy value for pulses shorter than 18µs the maximum amplitude seen by the amplifier for an 18µs pulse represents an upper bound on the amplifier input current.

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Conditions for maximum photocurrent</th>
<th>Conditions for minimum photocurrent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>950nm</td>
<td>400nm</td>
</tr>
<tr>
<td>Photodiode responsivity</td>
<td>0.6 AW⁻¹</td>
<td>0.15 AW⁻¹</td>
</tr>
<tr>
<td>Exposure duration or pulse width</td>
<td>18 µs</td>
<td>&gt;10 000s</td>
</tr>
<tr>
<td>MPE at wavelength and exposure duration</td>
<td>874 Wm²</td>
<td>0.01 Wm²</td>
</tr>
<tr>
<td>Power measured over 7mm diameter aperture</td>
<td>33.6mW</td>
<td>384nW</td>
</tr>
<tr>
<td>Resultant photocurrent</td>
<td>20.2mA</td>
<td>57.7nA</td>
</tr>
</tbody>
</table>

Table 4.3: Calculation of maximum and minimum photocurrents from a silicon photodiode

On the basis of these photocurrents the minimum gain required was 200, multiples of 20 from this give gains of $4 \times 10^3$, $80 \times 10^3$ and $1.6 \times 10^6$. It was necessary that gain increased in multiples of twenty so that increases in gain matched the dynamic range of the integrator in the interface module. The wider dynamic range of the detector head (factor of 200 between maximum and minimum output voltages) was necessary because the total energy measured could consist of a train of many low amplitude pulses. The head required sufficient range to reproduce such an input without noise problems.

The head gain was selected using a decimal counter. Pulses from the interface unit incremented the counter output which selected the appropriate resistor values using solid state switches. This counter was also used after the measurement to read back eight data bits identifying the head type and any apertures or attenuators which were
used. Each of the eight least significant counter outputs were connected via a series diode to the data output line (which was pulled low). Diodes were fitted or omitted to give the unit a unique identification code. Data was extracted serially by incrementing the counter and reading the returned data bit.

4.2.7 Noise in the photodiode head

The sources of noise in photodiodes have been discussed in Section 2.4.2.2. The noise voltage at the detector head output is a function of photodiode noise and detector head component noise, modified by the frequency response of the detector head. The performance of a standard transimpedance amplifier was investigated to guide the choice of a suitable operational amplifier. The effect of the pulse stretching network on the basic configuration was then investigated. Final verification of performance was obtained by measuring the noise voltage of the prototype.

Photodiode shunt resistance and stray capacitance affect the noise performance of the detector and amplifier combination. These effects are discussed in detail by Eppeldauer and Hardis [90] and Franco [93]. Figure 4.10 shows the photodiode and transimpedance amplifier circuit when all relevant physical and parasitic components are included. Operational amplifier noise sources are also included. All noise sources are assumed to be independent; their sum is therefore determined as the root sum of squares.

The transimpedance gain is given by:

\[ Z = \frac{R_F}{1 + j(2\pi f R_F C_F)} \]

This is equivalent to a first order low pass filter with corner frequency determined by \( R_F \) and \( C_F \). Photocurrent, photodiode shot noise current and operational amplifier noise current are all amplified by this factor to appear at the output as a voltage. The relative importance of each noise current source depends on the magnitude of the noise current and the specific spectral characteristics. For example operational amplifier current noise usually consists of a \( 1/f \) section at low frequencies (below 10-100Hz) and white noise at higher frequencies [93].
Johnson noise generated by $R_p$ is transferred to the output with unity gain. The spectral density is modified by the first order filter formed from $R_p$ and $C_F$. Increasing the value of $R_p$ causes an increase in the noise voltage as $R_p^{-0.5}$, whilst the transimpedance increases as $R_p$. The signal to noise ratio is therefore improved by using larger transimpedance values.

The voltage noise generated by the operational amplifier receives different gain from the current noise and the signal. Voltage noise is transferred to the output with the operational amplifier acting as a non-inverting voltage amplifier. The expression for the voltage noise gain in the circuit of Figure 4.10 is:

$$G = \frac{R_p + R_{SH}}{R_{SH}} \times \frac{1+\jmath 2\pi f \left( \frac{R_p R_{SH}}{R_p + R_{SH}} \right) (C_F + C_L + C_J)}{1+\jmath 2\pi f R_p C_F}$$

It is apparent that the diode shunt resistance, junction capacitance and stray capacitance influence the noise performance of the photodiode and amplifier combination. At low frequencies the noise gain is determined by $R_p$ and $R_{SH}$. For the photodiode used (S1223) the minimum shunt resistance is $2\,\Omega$, noise gain therefore remains effectively unity for all values of $R_p$. The second section of the expression for noise gain has both a pole and a zero. The zero frequency is determined by the parallel combination of shunt and feedback impedance and inevitably is lower than the pole frequency. The pole frequency equals that of the transimpedance gain. Figure 4.11 shows a Bode plot of the voltage noise gain and for comparison the transimpedance
Voltage noise gain increases at 20dB/decade from the zero frequency. The increase in voltage noise gain continues to the pole frequency where it reaches a constant value. At the pole frequency the transimpedance gain starts to decrease at 20dB/decade. The open loop gain of the operational amplifier is important in determining overall circuit behaviour in this region. If, as shown the voltage noise gain intersects the open loop gain above the pole frequency there will be a significant region of gain which is available to voltage noise, but the signal gain will be decreasing. Alternatively if the intersect is below the pole frequency then instability will be evident (rate of closure between open and closed loop gain exceeding 20dB/decade implies insufficient phase margin [93]).

It is possible to draw the following practical conclusions from the analysis:

- In the photodiode of interest and for feedback resistances of interest, the low frequency noise gain is negligible. Wideband operational amplifier noise levels are more significant than low frequency behaviour.
- The parallel combination of feedback resistor and diode shunt resistance is dominated by the feedback resistance in this application, the difference between zero and pole frequencies is a function of the difference between the diode and feedback capacitance.
Photodiode capacitance and stray capacitance affect the noise performance and may affect the stability.

Increasing the value of $C_r$ reduces the high frequency value of noise gain and if necessary will improve the stability by moving the pole frequency below the open loop gain intercept.

Increasing $C_r$ reduces the bandwidth available to the signal.

Minimising the diode and stray capacitance is important because it reduces the difference between pole and zero frequencies, thereby reducing the increase in noise gain at high frequency.

If stability is a problem then reducing diode and stray capacitance is important because it reduces the pole frequency and may move the noise gain and open loop gain intercept towards a lower rate of closure.

Resistor noise may be minimised by using metal film types in preference to carbon types. The effect of diode and stray capacitance may be reduced through the choice of component and layout. Low noise operational amplifiers considered were the OPA602 (FET input) with a current noise of 0.6 fA/Hz$^{0.5}$ and voltage noise of 13 nV/Hz$^{0.5}$ and an LT1028 (bipolar input) with current noise 4.7 pA/Hz$^{0.5}$ and voltage noise 1 nV/Hz$^{0.5}$. Wilson and Lyall [45] state that the voltage noise of an operational amplifier is usually the dominant noise source in wide band systems when combined with the effects of stray capacitance and diode shunt resistance. On this basis the LT1028 bipolar input device would be expected to have a superior noise performance.

The pulse stretching network affects the noise performance of the circuit. Without the isolating effect of the inductor and series resistor the charge storage capacitor would severely degrade the transimpedance amplifier stability and introduce significant voltage noise gain. Instead the inductor isolates the charge storage capacitor, also making the photodiode capacitance irrelevant to noise and stability considerations. The photodiode shunt resistance becomes largely irrelevant, the charge storage capacitor bypasses it at frequencies of interest. The stray capacitance associated with the inductor and series resistor may be neglected because the effects contributed are at frequencies above the open loop gain of the amplifier. The input circuit drawn to clarify voltage noise analysis simplifies to that shown in Figure 4.12. At resonance the
A series LCR circuit presents an impedance equal to the series resistor. Away from resonance the LCR circuit impedance is high. The series resistance determines the tuned circuit quality factor and hence the width of the resonant peak.

![Series LCR Circuit Diagram](image)

**Figure 4.12**: Pulse stretching head re-drawn to clarify noise analysis

For frequencies where the LCR circuit has a high impedance the noise voltage gain approximates to unity. Around the resonant frequency of the LCR tuned circuit the noise voltage gain is increased. Increasing the tuned circuit series resistance decreases the noise gain, but this is impractical because it affects the photodiode operating conditions. Increasing values of feedback resistance increase the noise voltage gain at the resonant peak and by decreasing the LCR circuit quality factor, increase the width of this peak.

The effect of the pulse stretching network on the noise performance was investigated using PSpice simulation. It was found that broadband noise predominated, with a peak in the noise voltage amplitude around 73kHz introduced by the pulse stretching circuit. Increasing the transimpedance gain increased the width of the peak around 73kHz, but calculation of r.m.s. noise below 100kHz showed that increasing transimpedance increased the signal to noise ratio; the relative increase in transimpedance was greater than the relative increase in noise. It is therefore an advantage to maximise the gain of the first stage rather than using a low transimpedance and relying on subsequent voltage gain. Noise performance of the first operational amplifier is critical.
The calculated values for each transimpedance resistance are shown in Table 4.4. These values will not necessarily reflect actual noise voltages because the manufacturer's operational amplifier models are not designed to simulate the true device noise behaviour. Comparison of values is valid because the intention is to investigate the effect of external passive components on the overall voltage noise transfer function. Neglecting the true noise contribution of the internal circuitry of the operational amplifier will only affect the overall noise magnitude.

<table>
<thead>
<tr>
<th>Transimpedance</th>
<th>Calculated noise voltage over 100kHz</th>
<th>Increase in transimpedance</th>
<th>Increase in noise</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>8.8μV r.m.s</td>
<td></td>
<td>21.5</td>
</tr>
<tr>
<td>4300</td>
<td>130μV r.m.s</td>
<td></td>
<td>19</td>
</tr>
<tr>
<td>82 000</td>
<td>1.08mV r.m.s</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.4: Simulated changes in noise from pulse stretching head.

The pulse stretching network degrades the noise performance of the basic transimpedance amplifier by introducing a peak of noise voltage gain. The reduced bandwidth required with the pulse stretching head compensates for the peak of noise voltage gain by reducing the wideband noise which would be an inevitable consequence of resolving short pulses. If the pulse stretching network was not used, the need for an amplifier capable of operation to above 100MHz would introduce greater noise. Noise in the remainder of the instrument would also become more significant because of the wider bandwidths required to process the much shorter pulses from the head.

4.2.8 The use of alternative photodiode types

The silicon photodiode detector head was designed for operation between 400nm and 950nm. Extension of the photodiode head design to other spectral regions requires the use of alternative photodiode types. Section 2.4.2.3 considered the alternatives for operation at wavelengths shorter than 400nm and longer than 950nm.
An InGaAs photodiode has superior performance to a germanium photodiode for near infrared operation [48,55]. Over the spectral region 700nm to 1050nm the minimum pulse width for which pulse duration is significant is 18µs and the maximum pulse repetition rate at which pulses must be individually resolved and counted is 55.6kHz. Exactly the same pulse stretching approach as used for the silicon photodiode may be applied. A typical InGaAs photodiode [63] has a rise time of 50ns and is therefore sufficiently fast for the application. Junction capacitance is higher than silicon devices, typically 20pF for a 1mm diameter device, with reverse bias of up to 20V being permissible. Shunt resistance is lower, typically 100MΩ for a 1mm diameter device. Interaction between the junction capacitance and shunt resistance would degrade the noise performance and stability in a standard transimpedance amplifier. Using the pulse stretching approach brings the advantage that the photodiode is isolated from the amplifier. The modified photodiode parameters would not therefore affect the noise or stability of the amplifier.

An InGaAs photodiode head would be suitable for the spectral region 950nm to 1500nm. The photodiode is usable to 1700nm, the long wavelength limit is imposed by the significant increase in MPE thresholds between 1500nm and 1800nm [3]. It becomes more appropriate to use a pyroelectric detector to measure the considerably increased pulse radiant exposures.

At the ultraviolet wavelengths of interest (180nm to 400nm) SiC, GaAsP and GaP photodiodes would be suitable and would provide the necessary intrinsic visible blind response. Schottky GaAsP photodiodes [92] are slow devices with a typical rise time of 3.5µs and terminal capacitance of 1.8nF. Maximum permissible reverse bias is 5V. Shunt resistance is typically 2GΩ. GaP devices [92] have comparable rise time and terminal capacitance and twice the shunt resistance. The isolating effect of the pulse stretching network would prevent the photodiode capacitance from being a problem. The slow rise time implies that the majority of pulse stretching for sub-microsecond pulses would be internal to the detector. It would be essential that recombination rates were low. The alternative photodiode type, SiC is a more ideal device. A 1mm diameter device has typically 195pF terminal capacitance and can withstand 20V of
reverse bias. Shunt resistance is extremely high; the dark current at 1V is typically 2fA, implying a shunt resistance of 500TΩ. The spectral response is less ideal; reaching a peak at approximately 250nm before decreasing to a cut off at approximately 400nm. This is less severe because of the increased MPE at longer wavelengths, but might introduce temperature sensitivity problems.

The primary problems associated with measurements at ultraviolet wavelengths are the need to resolve pulses with widths down to 100ns (Section 2.2.5) and the low irradiances corresponding to the MPE (Section 2.2.6). Implementing a full assessment capability for ultraviolet lasers would result in an unacceptable hardware overhead for all other lasers. It was shown in Section 2.2.5 that the maximum pulse repetition rate at which individual pulse energy must be measured was 31.8Hz. At higher repetition rates the total energy alone is significant in determining the radiation hazard.

A pragmatic approach to radiation hazard assessment of ultraviolet lasers would be to use a pulse stretching detector head to avoid the need to resolve short pulses. The user would be required to enter a value of pulse width. The pulse stretching approach would have the important effect of reducing noise by limiting the bandwidth required. Given the low maximum pulse repetition rate at which it was necessary to resolve pulses the head bandwidth could be limited to less than 1kHz. For such a low bandwidth a CR pulse stretching head could be more appropriate than the LCR design. Whichever pulse stretching method was used, it would be important that the photodiode exhibited minimal photogenerated carrier recombination.
4.3 DESIGN OF THE PYROELECTRIC DETECTOR HEAD

4.3.1 Introduction

A pyroelectric detector was used for laser radiation measurements over the spectral region 1.5\(\mu\text{m}\) to 10.6\(\mu\text{m}\). The increase in MPE values in this spectral region compared to those for shorter wavelengths means that the lower responsivity of the pyroelectric detector compared to photodiodes is less of a disadvantage.

Pyroelectric detectors operated in current mode are capable of resolving the temporal profile of pulses. The minimum resolvable pulse width is determined by the detector capacitance and the frequency response of the external amplifier. Pyroelectric detectors have no d.c. response, the responsivity decreases as a first order high pass filter below the thermal breakpoint (typically 0.25Hz). A pyroelectric detector is therefore unsuitable for c.w. radiation measurements. Distortion of long pulses, or pulse trains with a low repetition rate (the timescale being determined by the thermal time constant) will occur. A consequence of the lack of a steady state response from the detector is that all pulse train outputs stabilise to have zero average value.

The design process considered the modelling of pyroelectric detectors, the performance of a typical device, the methods and implementation of overcoming the limited low frequency response, the gain required in the detector head and the noise performance of the proposed design.

4.3.2 Pyroelectric detector electrical modelling

A model for the electrical parameters of a pyroelectric detector is shown in Figure 4.13. The current source models the charge generated as absorbed radiation heats the crystal. This current is not a direct analogue of the incident power. Thermal effects modify the relationship between the incident power and the detector output at low frequencies. The model concentrates on the electrical parameters because these are more significant for the design process than the thermal parameters. It is only possible to determine thermal parameters by selecting a detector from the limited range available commercially. Electrical parameters may be modified by the interface circuit design and have a significant impact on overall detector head performance.
Detector capacitance \( (C_p) \) originates from the two electrodes applied to the crystal, which forms an insulating dielectric. The resistor \( (R_t) \) represents the loss conductance of the crystal [75].

A pyroelectric detector may be operated in one of two modes [94], determined by the ratio of detector electrical time constant to optical pulse width. The detector capacitance is usually more significant than the load capacitance \( (C_L) \), but the input resistance of the external amplifier \( (R_i) \) is usually smaller than the crystal loss conductance. If the electrical time constant is much larger than the input pulse width (high value of load resistance) then the peak output voltage is proportional to the incident pulse energy, reaching a maximum value at the end of the pulse. This is termed integration mode operation. When the detector electrical time constant is much shorter than the input pulse width (low value of load resistance), the output voltage is proportional to the instantaneous incident irradiance. This is termed current mode operation. A transimpedance amplifier may be used to measure the detector output current. This presents a low impedance load to the detector and provides an output voltage proportional to the detector current. Limitations in the frequency response of the amplifier cause the effective input impedance to increase at high frequencies which may limit the bandwidth to below that implied by the detector electrical time constant.

4.3.3 Evaluation of practical devices

It was essential that the pyroelectric detector was operated in current mode to enable pulse temporal profiles to be resolved. Integration mode would not have provided sufficient information on the maximum pulse power or pulse width. The majority of commercially available pyroelectric detectors are intended for integration mode.
operation and have voltage amplifiers built in to the same package as the detector. This has the advantage of reducing EMI susceptibility, but prevents direct access to the detector. A more limited range of detector only packages are available. The detector selected for initial investigation (Eltec 400 series) had a sapphire window to enable tests to be made using visible radiation. In the final application an alternative window material would be required to provide transmission of wavelengths up to 10.6\,\mu m.

For the initial investigation of the detector performance a fixed gain transimpedance amplifier ($10 \times 10^6$ gain) was constructed and the detector connected directly to the input pins to minimise noise pickup. The Pockels Cell optical pulse generator (Appendix 3) was used in conjunction with an argon ion laser to provide pulses with constant pulse power. Losses through the optical system limited the maximum power incident on the pyroelectric detector to approximately 10\,mW at 514 nm. A fast storage oscilloscope (Gould DSO4072 100MHz) was used to record the amplified pyroelectric and monitor photodiode outputs. Figures 4.14 and 4.15 show the two signals for two pulse trains with different repetition rates, but pulse width constant at approximately 100\,$\mu$s. The overshoot which was apparent on the output was a result of slight instability in the transimpedance amplifier rather than a characteristic of the detector. In each case the pulse envelope was accurately resolved and the output stabilised to give a zero average value. For comparison Figure 4.16 shows the amplified detector output when irradiated by 150 ms pulses. The distortion introduced by the thermal time constant of the detector is evident. It was apparent that even for the long duration pulses the change in detector output signal at a pulse edge remained proportional to pulse power, the distortion only affected the subsequent pulse envelope. Inspection of the detector response to long pulses verified the manufacturer's claim of a 0.25Hz thermal breakpoint. The time constant of the thermal distortion was found to be approximately 0.65s.

Noise was apparent on all the oscilloscope traces. A portion of this was a result of amplification of Johnson noise from the detector and amplifier feedback resistor. The remainder was EMI. Improved screening of the detector output and transimpedance amplifier would greatly reduce the effects of EMI.
Figure 4.14: Response of the pyroelectric detector to low repetition rate pulse train. CH1 (optical input) 2mV/div, CH2 (pyroelectric output) 10mV/div, X 100μs/div

Figure 4.15: Response of the pyroelectric detector to high repetition rate pulse train. CH1 (optical input) 2mV/div, CH2 (pyroelectric output) 10mV/div, X 100μs/div

Figure 4.16: Response of the pyroelectric detector to a train of 150ms pulses. CH1 (optical input) 2mV/div, CH2 (pyroelectric output) 20mV/div, X 100ms/div.
4.3.4 Design of the pyroelectric detector head

The high frequency response of the detector head may be increased by using a wide bandwidth transimpedance amplifier design capable of maintaining a virtual earth at high frequencies. Cost and noise considerations, compounded by low detector responsivity when used in current mode place practical limitations on the frequency response which may be obtained.

In theory the thermal cut off frequency could be reduced by following the detector with an amplifier having gain increasing below the thermal break frequency. This would counteract the reduction in detector responsivity. Practically it is not possible to provide increasing gain to ever lower frequencies. Finite open loop gain inherent in practical operational amplifiers restricts the amount of low frequency gain available. The detector output would still tend to stabilise with zero average value. Low frequency boost would only extend the time taken for the detector to reach equilibrium. Errors would be introduced if a measurement was not made immediately the detector was exposed to laser radiation. This causes a problem with the instrument because the automatic range selection function makes sequential measurements to locate the optimum gain. Subsequent measurements would therefore be of different peak values. The advantage of the low frequency boost approach is that for a given low pulse repetition rate the distortion is reduced.

Instead of attempting to modify the frequency response of the detector head an alternative approach was adopted. Limited low frequency response affects only low repetition rate pulse trains. The loss of the d.c. component of the signal affects all pulse trains and is therefore a more significant detector limitation. A d.c. restoration approach, shown in block diagram form in Figure 4.17 was used. The effect of the circuit is to add a positive offset to the detector output such that the minimum value of the waveform is increased to zero volts at the output. A unipolar output voltage is provided under all pulse duty cycles and including the initial transient phase as the pyroelectric detector reaches thermal equilibrium. The total energy over a measurement period can then be measured by integrating the detector head output.
Figure 4.17: Block diagram of the pyroelectric detector head

The minimum pulse repetition rate (and by implication, the maximum pulse width) is determined primarily by the amount of distortion which is acceptable in the output waveform. It can be assumed that the hold time constant of the negative peak detector is much greater than the thermal time constant of the detector element. The positive offset added to the detector output therefore remains constant. With low repetition rate pulse trains as the detector output increases back towards zero volts between pulses the detector head output increases from the zero baseline. This leads to an overestimate of total energy and maximum power. It would be possible to compensate for this by matching the hold time constant and detector thermal time constant so that the offset voltage decayed at the same rate as the detector output increased. The disadvantage of such an approach is that during a long pulse both the detector output and the offset voltage would decrease. Pulse distortion would therefore be increased, with pulse energy being underestimated. It was preferable in this application to overestimate the total energy and maximum power in situations where the user inadvertently used the detector head on a low repetition rate pulse train. The overestimate would depend on the repetition rate, being most significant when the repetition rate was lower than the thermal time constant.

An additional factor determining the maximum pulse width (minimum pulse repetition rate) at which the pyroelectric detector is capable of operating is the dependency of MPE on pulse width. As pulse width increases the radiant exposure associated with
the MPE increases, but the instantaneous irradiance decreases. Noise may therefore become significant. The measurement of maximum irradiance will be most affected by noise. Total energy will be less affected because of the averaging effect of the integrator in the interface unit.

The maximum permissible error introduced by the distortion of long pulses was defined as being a 10% drop in detector output from the initial value. The detector used had a thermal time constant of 0.65s, maximum permissible pulse width was determined from:

\[ V(t) = V_{peak} \times e^{-\frac{t}{0.65}} \]

Giving \( t = 68\text{ms} \) for an output dropping to 90% of the maximum value. This was reduced to 50ms to ensure that devices with shorter than average thermal time constant did not introduce excessive distortion. A single 50ms pulse has a pulse irradiance MPE of approximately \( 53 \times 10^3 \text{ Wm}^{-2} \), corresponding to a power of 42mW through a 1mm diameter aperture. On the basis of the detector responsivity given by the manufacturer (1.1\( \mu \text{A/W} \)) this would correspond to a current of 46nA. It was likely that measurements of lower currents would be adversely affected by noise. A maximum pulse width of 50ms corresponds to a minimum pulse repetition rate of 20Hz.

The lower limit at which pulse resolution was necessary for MPE assessments was 100ns. To resolve such short pulses would require wide bandwidth electronics and would inevitably introduce noise problems. It was shown in Section 2.2.5 that for pulse repetition rates in excess of 674Hz the average exposure conditions apply. It is therefore only necessary to resolve pulses at repetition rates below 674Hz. At repetition rates in excess of 674Hz it would be possible to use the thermopile detector head to measure the average power. For lower repetition rates it would be necessary for the user to enter the value of pulse width (and repetition rate if pulses were not resolved by the thermopile detector head) so that the energy per pulse could be estimated. This would have the disadvantage that individual deviant pulses with greater than average energy would not necessarily be detected. An alternative would
be to use the pulse stretching approach as applied to the photodiode detector head. It would be essential that the time constant of the pulse stretching network was considerably shorter than the thermal time constant of the pyroelectric detector, or charge loss as the detector element cooled would introduce errors.

As a means of demonstrating the concept of a pyroelectric detector head with d.c. restoration a minimum pulse width of 50μs was adopted. This is sufficient to permit analysis of many industrial CO₂ laser processing systems, one of the major applications for this detector head. Pulse stretching was not implemented so that the performance of the d.c. restoration alone could be investigated.

The design of the peak detector was the same as used in the interface unit, but with the diode polarity reversed to acquire the maximum negative value. A standard operational amplifier subtractor circuit then subtracted the negative peak value from the signal, restoring the zero level. The negative peak detector was reset before each measurement to prevent interaction between subsequent measurements. Detector head gain was set using the same circuit as the photodiode head. Head identification data was read back to the interface unit serially using the same method as the photodiode detector head.

If it was necessary to extend the minimum pulse repetition rate downwards (or maximum pulse width upwards) then low frequency boost and d.c. restoration techniques could be combined. By following the low frequency boost with the d.c. restoration circuit the effect of the delay to reach thermal equilibrium would be minimised.

4.3.5 Determination of the gain required

The MPE irradiance is a minimum for 50ms pulses and a maximum for 50μs pulses. Two alternative measurement apertures are specified by the standard. For exposures longer than three seconds a 3.5mm diameter aperture is required, for pulses shorter than or equal to three seconds a 1mm diameter aperture is required. It is likely that measurements would be required with different apertures when assessing the conditions of single pulse exposure and average exposure to a pulse train. To
determine the minimum and maximum transimpedance gains it is assumed that a 1mm diameter aperture is required at 50ms and 3.5mm diameter aperture at 50μs. The detector responsivity is specified as 1.1μA/W over the entire spectral range. A minimum head output voltage of 20mV and a maximum of 4V was required. As with the silicon detector head the preferred minimum output voltage was 200mV. Table 4.5 contains the relevant factors in determining minimum and maximum detector output currents.

<table>
<thead>
<tr>
<th>MPE (Wm⁻²)</th>
<th>50ms pulse</th>
<th>50μs pulse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture diameter (mm)</td>
<td>1</td>
<td>3.5</td>
</tr>
<tr>
<td>Detector power (W)</td>
<td>41.6 × 10⁻³</td>
<td>192</td>
</tr>
<tr>
<td>Detector output current (A)</td>
<td>46 × 10⁻⁹</td>
<td>212 × 10⁻⁶</td>
</tr>
</tbody>
</table>

Table 4.5: Calculation of minimum and maximum detector output currents

The minimum transimpedance corresponded to the maximum detector output current, a 4V detector head output was required. The maximum transimpedance was required to obtain a 20mV detector head output. On this basis the minimum transimpedance required was 40 × 10³, and the maximum 437 × 10³. These calculations exclude the spectral region between 1.5μm and 1.8μm. In this region the MPE is constant at 10⁴ Jm⁻², significantly higher than elsewhere. To avoid detector damage (especially with the thermopile detector) it was decided that a neutral density filter would be used over this spectral region. The need for extended electrical dynamic response is therefore avoided.

As with the photodiode detector head it was not possible to achieve sufficient gain with a single transimpedance amplifier. Two transimpedance gains were used; 4300 and 82 × 10². A voltage amplifier with gains of either unity or 20 followed the transimpedance stage to provide extra gain. The range of gain available exceeded the requirements but retaining increments in multiples of twenty matched the integrator ranges.
4.3.6 Noise in the pyroelectric detector head

The noise behaviour of the pyroelectric detector head is similar to the basic photodiode transimpedance detector head discussed in Section 4.2.7. The noise generated by a transimpedance amplifier is a function of the operational amplifier, the feedback resistance and capacitance and the detector capacitance and resistance. The pyroelectric detector used has a parallel resistance in excess of $5\,\Omega$ and therefore the low frequency noise gain will be unity regardless of the feedback resistor value. Detector capacitance was typically 30pF. It was therefore necessary to use capacitance in parallel with the feedback resistance to reduce the noise gain at high frequencies and to ensure stability. Values were selected on test for each value of feedback resistance, the capacitance which just suppressed ringing on the head output for a square wave input was adopted.
4.4 DESIGN OF THE THERMOPILE DETECTOR HEAD

4.4.1 Introduction

The thermopile detector is required to supplement the pyroelectric detector for c.w and low repetition rate pulse train measurements between 1.5\(\mu\)m and 10.6\(\mu\)m. The pyroelectric detector introduces distortion to pulses significantly longer than 50ms and the limited responsivity introduces noise problems. Low cost thin film thermopiles are available with sufficient responsivity to respond to powers in the milliwatt range. The first order time constant of these thermopiles is typically 50ms which permits a maximum repetition rate for pulse resolution of approximately 3Hz. Improvement of the response speed of the thermopile detector is therefore essential.

The design process considered the electrical modelling of thermopile detectors, the analysis of suitable devices, the method of increasing the effective bandwidth of the detector, the implementation of the head, the gain required in the detector head and the noise performance of the proposed design.

4.4.2 Thermopile detector electrical modelling

Thermopile detectors may be modelled electrically using the circuit shown in Figure 4.18. Absorbed radiation is equivalent to the current source I, \(R_T\) and \(C_T\) model the thermal resistance to ambient and the thermal capacity of the detection element respectively. The voltage across \(R_T\) is analogous to the detector temperature and therefore proportional to the detector output voltage. The detector acts as a first order low pass filter with a cut off frequency determined by the values of \(R_T\) and \(C_T\).

![Thermopile detector electrical model](image)

Figure 4.18 : Thermopile detector electrical model
Speed of response and responsivity are interdependent. Responsivity may be increased by reducing the thermal conductivity between detector and ambient, for example by evacuating the enclosure or filling it with a gas having lower thermal conductivity than air [46]. This reduces energy loss from the thermocouples and enables the hot junctions to reach a higher temperature for a given incident power. The disadvantage is that the response speed of the detector is decreased; reduced thermal losses mean the detector takes longer to reach thermal equilibrium under incident radiation and longer to return to ambient after irradiation. Reducing the thermal conductivity also reduces the maximum permissible power incident on the detector before thermal damage occurs.

If pulses with a width shorter than the time taken for the detector to reach thermal equilibrium are measured then the energy of the pulse is integrated by the thermal capacity of the detector. Under these conditions the detector output pulse rise time equals the optical pulse width. A limiting factor for the rise time is the time taken for the energy absorbed by the black coating to transfer to the thermopile elements. Ultimately, for short pulses the energy is absorbed entirely in the coating and the heat transferred more slowly to the thermopile element. The fall time of the output pulse is controlled by the thermal time constant of the detector.

4.4.3 Evaluation of practical devices

Investigation of detector parameters concentrated on the spatial non-uniformity and frequency response of typical thin film thermopiles. These two parameters were critical to the performance of a detector head and were not satisfactorily documented by the manufacturer.

The method described in Appendix 4 was used to investigate the spatial non-uniformity of the detector. Figure 4.19 shows the amplified detector output for a scan through the centre of a Dexter Research 2MC device. The detector has significant spatial non-uniformity. Responsivity is greatest at the edge of the sensitive area and decreases towards the centre of the detector. This was a result of the detector being fabricated from a ring of junctions. Heat generated by the absorption of radiation in the centre of the detector must diffuse radially to the thermocouple hot junctions before a signal is
Figure 4.19: The variation in responsivity over a 2MC thermopile detector generated. The thermal resistance of the coating will cause some reduction in the temperature measured by the thermocouples under such conditions.

As an alternative a Dexter Research 6M thermopile was investigated. This has a 6mm diameter circular sensitive area, information from the manufacturer suggested a similar pattern of spatial non-uniformity to the 2MC device (Figure 4.20). Despite the overall non-uniformity it was possible to utilise just the central portion to obtain a more uniform spatial response. Figure 4.21 shows the spatial response of the detector measured using a 2.5mm diameter aperture to expose only the centre of the detector. The aperture was fabricated as part of a brass block into which the thermopile was mounted. This provided a stable thermal environment for the detector. Short term temperature fluctuations would otherwise affect c.w. measurements. Two disadvantages of this approach were the higher cost and the slower response speed of the larger detector. An additional problem became apparent when the stability of the detector under constant illumination was investigated.

A helium neon laser beam (2.4mW) was centred on the apertured 6M detector. The amplified detector output was then recorded for ten seconds on a Digital Storage Oscilloscope (DSO) using a one second timebase. The output was also recorded at half minute intervals on a digital voltmeter (DVM). It was found that the detector output increased to a maximum during the first second of exposure and then after
Figure 4.20: The variation in responsivity over a 6M thermopile.

Figure 4.21: The variation in responsivity over an apertured 6M thermopile.

Figure 4.22: The variation in the 6M output with time.
approximately five seconds started to decrease. After two and a half minutes the output stabilised. Immediately after the beam was interrupted the detector output decreased to be negative before returning to zero over approximately two minutes. Figure 4.22 shows the voltages recorded from the DVM.

The one second delay to reach a peak value was slower than should have been observed for a detector with 60ms time constant. A 60ms time constant implies a delay of 276ms to reach 99% of the peak value. The additional time delay was attributed to the time taken for heat to diffuse from the centre of the detector to the thermocouple hot junctions.

The gradual decrease in output voltage was attributed to conduction of heat along the thermocouple elements to the cold junctions. If a thermal resistance existed between the cold junctions and the metal case then the cold junction temperature would increase slightly until a final equilibrium was reached. This would reduce the temperature differential and therefore the detector output voltage.

The dependency of output voltage on duration of exposure for the 6M detector made it unsuitable for the intended application. Instead a 2MC detector was used. The 2MC detector showed no change of output voltage during illumination. Optical design was required to attenuate the incident radiation and reduce the spatial non-uniformity.

The optical pulse response of the 2MC detector was investigated using the single LED drive board described in Appendix 2. A square wave of approximately 1.2s period was used, the amplified detector output is shown in Figure 4.23. Detailed examination of the pulse edges showed a time constant in the order of 70ms with rise and fall times (10% to 90%) of approximately 160ms. This was longer than the value claimed by the manufacturer (40ms time constant).

Further information on the frequency response of the thermopile was obtained using the linear LED drive board (Appendix 1) with sinusoidal input signal. A full frequency response curve between 0.1Hz and 600Hz was obtained and is shown in Figure 4.24. The low pass action of the thermopile is evident. Estimation of the corner frequency from the graph gave corner frequency of 2.7Hz. This corresponds to a time constant...
of 60ms, in reasonable agreement with that measured from the pulse response. At higher frequencies a second order roll off is evident. It was estimated that this became effective above 63Hz. This second pole in the response may originate from the delay in conduction of energy from the coating to the thermopile elements. The dominant, low frequency pole is associated with the thermal capacitance of the elements.

The thermal lag of the black coating was investigated using short pulses from the linear LED drive board (Appendix 1). It was firstly verified that the thermopile amplifier had sufficient bandwidth to reproduce all the test pulses by injecting the pulse signal directly to the amplifier input. The amplified thermopile output was then recorded simultaneously with the LED drive voltage for a 1ms pulse and a 50ms pulse. Figures 4.25 and 4.26 show the results. For the 50ms pulse the detector output increased over the duration of the optical pulse. This corresponded to energy being integrated in the thermocouple elements rather than the coating. For the 1ms pulse the detector output continued to rise after the end of the optical pulse. The delay between input and response originates in the thermal lag introduced by heat conduction through the black coating. The implication is that energy is absorbed predominantly on the surface of the coating rather than close to the thermopile elements. Noise was significant on this trace because of the very low average power of the optical input and consequent high gain which was required.
This thermal behaviour is significant in two respects:

1. For short pulses the detector will not give a maximum output proportional to the incident pulse energy, the total energy will still be recorded accurately because heat conduction from the coating is predominantly into the detector. The can is filled with argon to limit conduction losses to ambient [79].

2. The detector short pulse damage threshold will be determined by the coating rather than the substrate. It is the coating which will reach the highest maximum temperature when high energy short pulses are incident. This was discussed in the previous section.

4.4.4 Design of the thermopile detector head

The effective bandwidth of the thermopile detector can be increased by following the detector with a filter having complementary frequency characteristics to the detector. A gain which increases at 20dB/decade above the thermal cut off frequency of the detector is required to counteract the first order low pass filter inherent in the detector. This concept was applied by Brinkworth and Hughes [95] to increase the response rate of a solar pyranometer. The circuit configuration was not suitable for direct application to thin film thermopiles because the operational amplifier was used in inverting mode. It is preferable to measure the thermopile output voltage using the non-inverting operational amplifier input. This is necessary because the high internal
resistance of thin film thermopiles introduces errors if current is drawn from the detector. An additional advantage is that variations in the thermopile resistance with temperature or between devices cannot affect the filter characteristics.

The circuit used for the filter is shown in Figure 4.27. Figure 4.28 shows the frequency response of the filter as simulated using PSpice. At low frequencies the capacitors have negligible effect. Low frequency gain is controlled by the ratio of R1 to the sum of R2, R3 and R4. f₁ is controlled by R2 and C2. R3 permits fine adjustment of f₁ so that the onset of boost exactly matches the thermal time constant of the detector. R3 was adjusted with the detector exposed to a 20Hz optical square wave. Lower than ideal values of R3 gave an output with rounded corners, higher than ideal values caused overshoot on the output. Fine adjustment allows for device to device variations in the thermal time constant. Circuit gain increases to f₂ (controlled by R4 and C2) and is then nominally constant to f₃ (controlled by R1 and C1). This approach was preferred to one in which amplifier gain increased to f₃ because it combined adequate increases in rise time for pulse widths of interest without introducing excessive noise. Above f₃ the amplifier gain reduces at 20dB/decade to unity, ultimately the circuit gain is rolled off by the open loop gain of the operational amplifier. The detector and filter combination has a -3dB point around 70Hz.

![Figure 4.27: Circuit of the filter used with the thermopile detector](image)
A pyroelectric detector may be used for the measurement of pulses with width substantially shorter than 50ms at repetition rates lower than 20Hz, but the total energy will be overestimated. In these cases the thermopile detector will correctly measure the total energy but pulse width measurement will not be possible. The energy of the short pulse will be integrated by the thermal capacity of the element giving a maximum detector output voltage proportional to the incident pulse energy. The detector output pulse rise time approximates to the incident pulse width under these conditions. The fall time of the output pulse is controlled by the thermal time constant of the detector. A limiting factor for the rise time is the time taken for energy absorbed by the black coating to transfer to the thermopile elements. The amplifier rise time must be shorter than the minimum detector output rise time which could be encountered. If this is not the case then the maximum detector head output voltage will not equal the maximum detector output voltage and the incident pulse energy will not be correctly measured. Including the region of constant gain to \( f_3 \) in the filter provides sufficient amplifier bandwidth to respond to all detector output rise times.
4.4.5 Thermopile detector head gain

The filter gain was fixed, variations in head gain were implemented by a second voltage amplification stage. Irradiances corresponding to the MPE were at or above the manufacturer's recommended maximum (1000Wm⁻²). Before the thermopile detector head could be used for MPE assessments a method of optically attenuating the incident radiation would be required. For the purposes of testing the thermopile head design the second amplifier had gains of unity and twenty. The filter provided a low frequency gain of approximately ten. Final values of gain could be defined once the transfer characteristics of the optics were known. Selection of head gain and identification of the head type was achieved in the same way as the photodiode head.

4.4.6 Thermopile detector head noise considerations

The frequency boost associated with the filter increases the output voltage noise in comparison to an amplifier having constant gain. It is therefore undesirable to add more high frequency boost than necessary. Over the frequency range of interest, 50Hz noise pickup from the a.c. mains supply is a particular problem. To minimise this source of interference it was necessary that the filter circuit was mounted close to the detector with the connections to detector enclosing minimum area. Internal noise sources include the Johnson noise of the thermopile detector and other resistors, and the noise generated by the operational amplifier. The increased filter gain at high frequencies will increase the output noise voltage above that expected from white noise calculations. Despite that it was not anticipated that Johnson noise and operational amplifier noise would cause problems because of the limited overall bandwidth of the circuit. For example, over 10kHz the r.m.s. noise generated by the thermopile resistance would be approximately 1µV, equivalent to 50nW incident on the detector. The powers incident on the detector were far in excess of this.
4.5 OPTICAL DESIGN

4.5.1 Introduction

The design work concentrated primarily on the electronic optimisation of detector performance, however the optical design is an important aspect of any detector system. Some points relevant to the detector optics are; limiting detector angle of acceptance, defining measurement aperture diameters, minimising detector sensitivity to the position of incident radiation and ensuring that the detector remains linear over the power and energy ranges considered. The following sections consider these optical aspects of detector performance.

4.5.2 Angle of acceptance

The detectors were housed in small metal cans with windows which gave an angle of view in the range 60° to 100° (full angle). Laser radiation is usually emitted from a source subtending a relatively small angle at the detector (<1°). Large angles of acceptance increase the proportion of background light included in the measurement. If the background light forms a significant part of the total measured radiation then errors may be introduced, especially by fluctuations in background light. Even a constant background light level will reduce the resolution with which the laser radiation can be measured. Angle of acceptance must not be reduced too far or alignment becomes very critical. It is also necessary to maintain sufficient angle of acceptance to ensure that all radiation from extended sources is included where appropriate (see Section 2.2.7). The largest angle of acceptance required is $\alpha_{\text{min}}$ (0.1 radians, 5.7°), this being the full angle [96].

A simple solution is to use a single convex lens to focus the radiation onto the detector. The choice of lens focal length determines the angle of acceptance for the system. There are three problems with this approach:

1. The lens focuses a laser beam to a small spot with a very high local irradiance. This may be sufficient to cause non-linearity or even damage the detector. Focused spots may be avoided by placing the detector out of the focal plane, but this is at the expense of reduced angle of acceptance.
2. For lenses with practical focal lengths the angle of acceptance is low (4° full angle typically).

3. A lens has a refractive index which is wavelength dependent and introduces an additional spectral dependency into the optical system.

Despite the limitations a lens was used for the prototype photodiode detector head. Lenses were readily available so testing of the head was not delayed by the design of more complex optical systems.

An alternative optical arrangement is the use of a non-imaging reflective optical concentrator. This would be capable of providing a wider angle of acceptance without focusing the radiation onto the detector. Fabricating the concentrator from aluminium would provide a wide spectral response instead of the limited spectral response of lenses. The concept was not explored in the prototype because a lens was sufficient for testing the instrument.

4.5.3 Measurement aperture

The standard [3] defines specific circular measurement aperture diameters. Suitable diameter circular apertures for the spectral range considered range between 1mm and 7mm. A 1mm aperture may be defined by using a detector with appropriate diameter, for accuracy it is preferable if the detector is slightly oversize as a precision aperture may then be fitted to remove detector to detector variations. It is less practical to take such an approach with the 7mm diameter aperture. Suitable diameter detectors are available but at a higher cost and with slower response time. It is preferable to condense the incoming radiation measured over a suitable aperture down to a smaller detector area. The measurement aperture may then be defined using a circular aperture mounted over the lens or input to the concentrator.

4.5.4 Minimising detector spatial non-uniformity

To ensure reproducible results the responsivity over the detector should be uniform. Variations in detector responsivity over the sensitive area are of particular concern with thermopile detectors. Experimentation has shown significant variations, probably
related to the arrangement of the thermocouple junctions beneath the coating. For all
detector types, interference phenomena caused by the window may be another source
of error, Boivin [97] illustrates this for silicon photodiodes.

In the prototype detector heads it was not found necessary to address spatial
non-uniformity during the testing process. In a final design of detector head the
interference phenomena could be avoided using a wedged detector window or a
diffuser [97]. A diffuser provides some attenuation which may be beneficial in certain
spectral regions. The wedged window is a more appropriate solution where a
reduction in responsivity cannot be tolerated.

Irradiating only the central portion of the detector and avoiding focusing to small spots
on the detector reduces the problem of spatial non-uniformity. The non-imaging
reflective concentrator is preferable to a lens on this basis.

4.5.5 Ensuring detector linearity

Making measurements at radiation levels corresponding to the MPE raises issues of
detector non-linearity or damage for photodiodes exposed to short pulses and the
thermopile detector generally. The pyroelectric detector has a greater damage
threshold. Non-linearity or damage at the MPE is only possible for certain pulse
widths in the spectral range 1.5µm to 2.6µm where the front surface electrode may be
damaged.

For all spectral regions in which photodiodes are applicable, neutral density filters
(NDF) are available. A reflective type on a quartz substrate is suitable for ultraviolet
operation. For visible and near infrared operation an absorptive glass filter provides
flatter spectral response [98]. Alternatively a diffuser could be used.

The use of an optical attenuator to prevent detector damage from the high pulse
irradiance of short pulses has the advantage of reducing the background radiation by a
similar factor. Reduction of background radiation is particularly important for single
short pulses where the MPE energy is small. Electronic noise becomes important for
the measurement of short pulses because the optical attenuator inevitable reduces the
average power. The use of a pulse stretching photodiode detector head design is of benefit because of the reduced electronic bandwidth and associated reduction of noise.

A small integrating sphere was considered as a method of reducing the energy reaching the thermopile. This has the additional advantage of removing sensitivity to incident beam position. For the pyroelectric detector it may be necessary to attenuate short pulses in the spectral range 1.5\,\mu m to 2.6\,\mu m to avoid damage to the front surface electrode. This is just within the spectral range of absorptive glass (BK7) neutral density filters (BK7 exhibits monotonically decreasing transmission above 2\,\mu m and extinction above 2.7\,\mu m). To avoid cracking of the detector the incident radiation must not be concentrated using a lens. The reflective concentrator would be a suitable method of condensing the radiation from the measurement aperture onto the detector and has the advantage of being spectrally insensitive.

4.5.6 Excluding background radiation

Designing the instrument to have a wide dynamic range is of use only if the highest sensitivity ranges can be used without the instrument being swamped by ambient radiation. If the background radiation forms a significant part of the total measured value then the resolution with which the laser radiation can be measured is reduced. It is apparent in Table 2.3 that the ultraviolet wavelength regions have the lowest effective MPE irradiances. The removal of background radiation will be especially important for these wavelengths.

Two optical approaches to controlling the effect of background radiation are appropriate:

1. Restrict the detector field of view. Laser radiation is generally emitted from a localised area, whereas background radiation is emitted over a large area. A large field of view increases the relative contribution of the background radiation. The lower limit on the field of view is imposed by the increased potential for alignment errors and the need to ensure that radiation from an entire extended source is included in a measurement.
2. Limit the detector spectral response. If the detector is sensitive to wavelengths beyond the intended spectral range then the relative contribution of background radiation will increase. A narrowband interference filter could be used for assessment of a specific laser. Broadband filters would be suitable for measurements over a wider spectral range. The drawbacks of this approach include high cost, a dependency of filter spectral response on the angle of incidence and a lack of suitable substrates for ultraviolet spectral regions. A better solution is to select a detector with intrinsic physical characteristics which limit the spectral response.

A background subtraction function may also be required in the instrument. For every assessment one measurement is performed with the detector in the laser radiation and a second with the detector exposed to ambient radiation alone. The difference between the measurements corresponds to the true laser radiation. A background subtraction function will compensate for offsets in the electronic circuitry and for background radiation. Background subtraction does not address the problem of limited resolution if the background radiation forms a significant proportion of the measured radiation. Errors are also introduced if the background radiation level changes between the laser and ambient measurements. It is therefore preferable to use the detector spectral response and controlled field of view to eliminate the majority of background radiation. The background subtraction function then eliminates the effects of the residual background radiation.
4.6 SUMMARY

Silicon, thermopile and pyroelectric detector head modules were designed and constructed for the prototype instrument. In each case an electrical model of the detector was presented. Practical detectors were investigated so that an optimum device could be selected.

The silicon detector head was representative of a more general design which could be applied to other photodiode types. A novel design was adopted; an LCR circuit was used at the input to a transimpedance amplifier. The energy of short pulses was conserved by the LCR circuit whilst the output pulse width was kept constant. For long pulses the LCR circuit had negligible effect. Fixing the detector head output pulse width using the LCR circuit ensured that for short pulses the maximum output voltage corresponds to the pulse energy. For longer pulses the maximum output voltage is proportional to pulse power. This changeover is in accordance with the general requirement in the standards to measure the energy of short pulses and the power of longer pulses. The pulse stretching design increased the output noise in comparison to that of a transimpedance amplifier of comparable bandwidth, but it was shown by simulation that the increase in noise was far less than would be generated in a detector head capable of resolving short pulses.

The optimum method of interfacing to the pyroelectric detector was considered. Two alternatives were to increase the low frequency gain to compensate for the decrease in low frequency detector responsivity or to use a d.c. restoration circuit to provide a unipolar output signal. The d.c. restoration circuit was adopted because the lack of a true d.c. detector response affects all measurements, whereas the reduction in low frequency responsivity only affects low repetition rate pulse trains. A suitable circuit was designed to implement the d.c. restoration. The pulse distortion introduced by the reduction in the low frequency responsivity of the detector limited the minimum pulse repetition rate to 20Hz.

The thermopile detector head was designed to operate with optical inputs ranging from c.w. to 20Hz pulse trains. It was necessary to increase the apparent bandwidth of the detector to resolve such pulses. A filter was designed with a frequency response
characteristic complementary to that of the detector. The design differed from previous implementations because the detector was isolated from the filter. This ensured that detector resistance variation with detector temperature or between detectors could not influence the filter characteristics. Implementing a frequency boost function inevitably increased the output noise of the detector head, but the relatively large optical signals to be measured ensured that this was not a problem.

The optical design of the detector heads concerned methods of defining the angle of acceptance and measurement aperture, controlling spatial non-uniformity, avoiding detector damage or non-linearity and excluding background radiation. It was not necessary to adopt all the optical design requirements for the purposes of testing the prototype.
5 DESIGN OF THE INSTRUMENT

5.1 INTRODUCTION

In Chapter 4 the design of the detector head modules was described. Detector heads convert the incident radiation into an electronic signal. Each detector head performs initial analogue signal processing to provide a standard format signal for the interface unit. The interface unit measures the relevant parameters of the detector head output. These are the total energy, maximum energy or power as appropriate, total radiation present time and the number of pulses over the measurement duration. A means of detecting possible detector overload is implemented. To maximise the flexibility of the interface unit the hardware functions are kept generic with minimal optimisation to current laser hazard assessment requirements.

Before a measurement data is transmitted to the detector head to set the gain, information identifying the detector head type and configuration is read after each measurement. All the measurement data is transmitted serially using a standard RS232 link to the computer.

The external computer has control over the measurement process and provides the user interface. Guidance to the user, calculation of the appropriate MPE, comparison to the measured value and display of the results are performed by the computer. Concentrating the majority of task specific functionality in software maintains flexibility. This facilitates future updates to accommodate changes in the standards or the development of new detector heads.
5.2 DESIGN OF THE INTERFACE UNIT

5.2.1 Introduction

A block diagram of the interface unit is shown in Figure 5.1. The input to the unit from a detector head is a voltage in the range 0V to 4V. A peak detector, an overload detector and an integrator extract the necessary parameters from the input signal. The bandwidth required in the interface unit was determined by the design of the detector heads. The minimum pulse width from a detector head was approximately 10μs with the rise time limited to a minimum of 5μs. This implies the need for a bandwidth of 70kHz. A microcontroller controls the measurement process. Measurement data is transferred to and from the computer along a serial (RS232) link. Using a standard serial data link avoided restricting the interface unit to the use of a single type of computer.

The following sections examine the design of the major functional blocks comprising the interface unit.

5.2.2 Microcontroller

An 8-bit microcontroller was used to control the operation of the interface unit and to interface to the computer via a serial link. A Zilog Z86E08 device was used. This is from a family of low cost microcontrollers which have ample processing power for the simple interfacing, control and data handling functions required. A specific advantage of the device was the availability of an interrupt structure and two on chip counter/timers which made pulse counting and duration measurement straightforward.

One counter/timer is used to count pulses, the other is used as a timer. Since timers are required in several places during the program (though not simultaneously) the interrupt is redirected to the appropriate subroutine according to a value stored in a register pair. Before each use the timer is initialised and the address of the specific subroutine for handling the timer function is written to the redirection register pair.

The microcontroller had insufficient data input and output lines to directly address all the necessary functions. Since the speed of data transfer was not of primary importance a bus structure was used to increase the interface capability. A single
Figure 5.1: Block diagram of the interface unit.
bi-directional data bus with a uni-directional control bus was used. The control bus selected which bank of data lines had access to the microcontroller. Interrupt sources were applied directly to the microcontroller to ensure reliable and rapid service.

Following power up the ports and timers are initialised and the interrupt priorities are defined. The microcontroller then waits in a loop until an interrupt is generated by a transition on the serial data line. A single byte is read from the serial line and stored in a register. The timer is used to determine the intervals at which the data line is sampled, the prototype received data at 9600 baud. The serial routines were based on example code contained in the Zilog application notes [99].

The value of the byte received corresponds to the measurement range to be used by the detector head. Both detector head and interface unit are reset, a number of pulses corresponding to the required range are transmitted to the head. Component values in the head are selected so that the gain increases by a factor of approximately twenty with each increase in gain.

A second reset of the interface unit is performed, this lasts for 200ms and ensures that the integrator and peak detector capacitors are fully discharged. The interface unit is maintained in hold mode during and after this reset to ensure that any input signal does not cause drift of the initial conditions. The duration of the reset pulse and the one second measurement period is controlled using one of the microcontroller timers.

During the measurement period the SIGNAL PRESENT comparator output is used as the gate control for the second counter timer and generates an interrupt on each rising edge. The rising edge interrupt is used to count pulses. A register pair is incremented on each rising edge; this has a maximum count value of 65536, the pulse stretching design of the detector heads ensures that this cannot be exceeded. The gated counter has a resolution of 1μs. For every 255μs of signal present the counter overflows and resets to zero. The interrupt so generated increments a second register pair which cannot overflow during the one second measurement period.

On completion of the measurement period the hardware "hold" line is immediately re-asserted. Three analogue values are digitised by selecting each input sequentially
(integrator output, peak detector output and head temperature sensor output) and using a standard routine to perform the analogue to digital conversion and data transfer. The twelve bits of data are extracted MSB first and stored in two sequential bytes.

Single bytes containing the integrator range and detector overload status flag are then read from the hardware, followed by the detector and aperture type from the head. Data from the head is transferred serially by applying clock pulses and reading the returned data bits.

The measurement data is stored in a contiguous string of bytes. These are transmitted sequentially to the computer. On completion of the serial data transfer the program returns to the initial loop awaiting another start byte.

5.2.3 Peak detection

The peak detector records the maximum detector head output voltage. This value is proportional to the maximum power, or maximum pulse energy if the incident pulse is shorter than 18μs with the photodiode detector head. It is essential that the peak detector circuit can capture the maximum value of the shortest input pulse (approximately 10μs wide). Once a peak has been acquired the voltage must be held with negligible decrease until the end of a measurement period. At the most basic level a peak detector consists of a half wave rectifier connected to a capacitor. The effect of non-zero forward voltage drop of practical diodes must be overcome for the circuit to be of use for the signal levels of interest. An operational amplifier may be used in conjunction with diodes to approximate an ideal half wave rectifier. To avoid the capacitor becoming discharged a buffer is used to measure the capacitor voltage. A variety of implementations of these basic functions have been described [100,101,102,103]. The final circuit is shown in Figure 5.2 and draws on aspects of these implementations to provide an optimal solution for this application.

The ability to capture short pulses and the need for minimal decrease in hold capacitor voltage impose contradictory requirements on the hold capacitor value. Rapid peak acquisition requires a small hold capacitor value, minimal decrease in peak hold
voltage requires a large hold capacitor value. A hold capacitor value of 100nF was used which gave stable hold characteristics when combined with a suitable buffer amplifier. The hold capacitor introduces a phase lag in the feedback path of the first operational amplifier (OA1). In combination with the phase lag of the buffer (OA2) this degrades the stability of the circuit and overshoot becomes apparent. Isolating the hold capacitor (C1) with a low value resistor (R5, 22Ω) reduces this problem. It was found that using values larger than 22Ω did not reduce overshoot further and started to degrade the speed with which pulses could be acquired. An AD712 dual operational amplifier was used to implement the half wave rectifier and buffer stages. This device has a fast settling time (1μs), low offset voltage (0.3mV typical) and low bias current (75pA maximum). It was therefore suited to both functions. Bleszynski [101] and Catto [103] recommend the use of an RC series circuit across D1 to provide compensation for the phase shift inherent in the feedback loop. It was found to be unnecessary when using the AD712, isolation of the hold capacitor was more beneficial in ensuring stability. The recommendation to use Schottky diodes for D1 and D2 given by Bleszynski [101] was adopted. This improved the accuracy and bandwidth of the circuit. The increased hold capacitor discharge rate caused by the greater reverse leakage of Schottky diodes was overcome using a circuit modification given by Clayton and Newby [100]. R4 and D3 are added, the buffer (OA2) maintains the voltage across D3 close to zero thereby eliminating leakage current. A standard
silicon signal diode for D3 was found satisfactory. A solid state switch resets the peak detector before each measurement.

5.2.4 Integrator

Integrating the input voltage from the detector head provides a measurement of the radiant exposure received by the detector over the measurement period. In the prototype instrument the use of a one second measurement period meant that a measurement of radiant exposure was exactly equivalent to the irradiance averaged over one second. Analogue and digital approaches to the integrator function were considered. The digital approach would use a fast analogue to digital converter (ADC) to digitise the input voltage. In order that total energy was accurately recorded the ADC would need to sample at 1MHz or greater. Adding each sample would give the total energy, samples could also be stored in memory for subsequent analysis. This would permit detailed analysis of the measured radiation but incurs a significant hardware overhead. Even if eight bit sample resolution was adequate the cost of a fast ADC and 1M byte of memory would be significant. The data would require post processing to extract the maximum values, the total on-time and the number of pulses. This processing would have to be local to the instrument to avoid long delays as the data was transferred over the RS232 link. The volume of information available by fully digitising the input waveform exceeds the information available in the standards on the hazard assessment of non-standard pulse trains. There is therefore no advantage in acquiring the extra data and the hardware overhead of the digital approach is a disadvantage. Analogue integrators were considered as a more suitable alternative.

Three integrator configurations were considered; the standard Miller implementation (an inverting operational amplifier with a feedback capacitor rather than a resistor) and two alternative designs with different attributes optimised. Saha [104] proposed a circuit to extend the time constant of an integrator whilst improving the d.c. stability of the circuit to minimise drift. Nandi and Sarker [105] proposed a design with improved high frequency response. Comparison was performed using a PSpice simulation of the circuits. Component values were selected to give all three integrator configurations an identical time constant.
The frequency response was evaluated by using a swept 50mV sinusoid input over the frequency range 1Hz to 1MHz and an integrator time constant of 0.01s. A capacitor value of 100nF was used in all three circuits and resistance values were calculated to maintain a 0.01s time constant. It was important to keep capacitance constant as this was most likely to affect the amplifier high frequency characteristics. An ideal integrator maintains -90° phase shift between the input and output signals. The phase shift at 100kHz was used as a measure of the integrator high frequency performance. This frequency corresponded to the upper limit of frequencies to which the integrator would have to respond. Table 5.1 summarises the results of the three circuits.

<table>
<thead>
<tr>
<th>Circuit configuration</th>
<th>Phase at 100kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Miller</td>
<td>7°</td>
</tr>
<tr>
<td>Nandi and Sarker</td>
<td>-89°</td>
</tr>
<tr>
<td>Saha</td>
<td>46°</td>
</tr>
</tbody>
</table>

Table 5.1: Comparison of high frequency response of integrator configurations

It is evident that the circuit proposed by Nandi and Sarker has superior high frequency response. The circuit proposed by Saha has the worst frequency response. In the intended application the accuracy of integration was of greater interest than the dynamic performance. It was important that total charge over the measurement period was accurately stored, short term errors as the circuit settled were less significant. To compare the response of the three circuits, two extremes of pulse width with two extremes of capacitance were compared. The pulse energy was maintained constant. Table 5.2 contains the results.

In all cases the input pulse had a constant maximum value and rise and fall times equal to 1μs. The integrator output voltage was recorded immediately after the end of the input pulse so that the effects of drift were excluded. The circuit proposed by Nandi and Sarker gave close to the theoretical output voltage for each pulse condition. The limited high frequency response of the circuit proposed by Saha was manifested in significant error for the 20μs pulse. This configuration is therefore unsuitable for the intended application. It is apparent that despite the poor phase performance of the Miller circuit, it retained good accuracy of charge integration. The circuit relies on maintaining a virtual earth at the inverting input to the operational amplifier. This is
achieved by feeding sufficient charge from the output back to the input via the capacitor so that charge injected via the resistor is exactly cancelled. Dynamic limitations in the operational amplifier bandwidth or slew rate will cause transient deviations from zero at the virtual earth. If the deviations are small in comparison to the input voltage this will have minimal effect and the virtual earth will be restored shortly after the end of the pulse. It is therefore possible for the Miller integrator to have relatively poor dynamic performance (as shown in Table 5.1), whilst retaining good accuracy (as shown in Table 5.2). In the integrator proposed by Saha the charge storage capacitor is isolated from the input by an operational amplifier. If this amplifier has insufficient bandwidth or slew rate to follow the input then the charge will be lost because there is no short term storage as the amplifier settles.

<table>
<thead>
<tr>
<th>Pulse voltage (V)</th>
<th>Pulse width (s)</th>
<th>Integrator capacitance (nF)</th>
<th>Miller</th>
<th>Nandi and Sarker</th>
<th>Saha</th>
</tr>
</thead>
<tbody>
<tr>
<td>$5 \times 10^{-3}$</td>
<td>0.1</td>
<td>10</td>
<td>-496</td>
<td>501</td>
<td>-497</td>
</tr>
<tr>
<td>$5 \times 10^{-3}$</td>
<td>0.1</td>
<td>1000</td>
<td>-4.97</td>
<td>5.01</td>
<td>4.97</td>
</tr>
<tr>
<td>25</td>
<td>$20 \times 10^{-6}$</td>
<td>10</td>
<td>495</td>
<td>500</td>
<td>-98</td>
</tr>
<tr>
<td>25</td>
<td>$20 \times 10^{-6}$</td>
<td>1000</td>
<td>4.98</td>
<td>5.00</td>
<td>-1.02</td>
</tr>
</tbody>
</table>

Table 5.2: Pulse response of different integrator configurations

The requirement for high frequency performance dictated that either the Miller or Nandi and Sarker configuration be used. Consideration was then given to the low frequency stability of the alternatives. A lack of low frequency stability is manifested by drift in the output voltage. Excessive output drift would reduce the resolution of a laser radiation measurement, but aiming for extremely low output drift was unnecessary. The background subtraction function is capable of removing the effects of background radiation and limited amounts of integrator drift.

Output drift in the Miller integrator originates in the bias current and offset voltage of the operational amplifier and is given by:

$$\frac{d(V_{out})}{dt} = \pm \frac{V_{offset}}{R \times C} + \frac{I_{bias}}{C}$$
An operational amplifier combining low offset voltage and bias current is necessary to minimise drift. An LT1097 device is suited to the application because the typical offset voltage is 50μV with a typical bias current of 250pA. For the typical component values of 100kΩ and 100nF the offset voltage contribution dominates the drift so there is no benefit in using FET input devices with lower bias currents but higher offset voltages. Furthermore the LT1097, being a bipolar device has a more stable bias current-temperature characteristic. Over a one second measurement the typical drift using these representative component values would be 7.5mV.

The causes of output voltage drift in the circuit proposed by Nandi and Sarker were expected to be more complex. Operational amplifier offset voltage and bias current would still contribute, non-ideal matching of the components in the feedback loop was also expected to be significant. The sensitivity of output voltage drift to component mismatch was investigated using PSpice to simulate the circuit output when resistor values were individually modified by 1%. It was found that a 1% mismatch caused severe drift in the integrator output voltage when combined with an operational amplifier offset of 50μV. The effect of the amplifier offset voltage was exacerbated by the component mismatch such that the integrator output drifted from zero to saturation in approximately two seconds when a 100nF capacitor was used. It would be complex and expensive to match components to better than 1% in a practical design and the consequent drift was unacceptable.

A Miller integrator was selected as the most suitable integrator implementation. The basic circuit was modified by including an automatic ranging function. The integrator required several ranges to permit accurate measurement of the extremes of radiant exposure which were anticipated. It was possible for the integrator range to be determined automatically using a simple voltage threshold to increment the range. An increase in the integrator range reduces the integrator output voltage and cannot therefore cause an overload. Suitable choice of the voltage threshold and the capacitor values ensures that the integrator output voltage cannot fall so low as to compromise the resolution of the analogue to digital conversion. By contrast an increase in detector head range increases the probability of electronic saturation because it increases the detector head output voltage. Consequently it is only possible to
determine whether the head gain should be increased at the end of a measurement. The best method of selecting the detector head gain was therefore to perform a series of measurements starting with minimum gain and using the computer to determine from the measured values whether an increase in gain was appropriate. Matching the integrator ranges to the increments in detector head gain made it possible to make the integrator range selection automatic. This was preferable to controlling both the head gain and integrator range by the computer. A large number of measurements could then have been required to locate the optimum combination of detector head gain and integrator range.

Physical restrictions on the number of capacitors used in the integrator and the available values restricted the ratio of maximum to minimum integrator range to a factor of twenty. Larger capacitance values were considered impractical because of the increased physical volume and leakage current. It was not practical to increase the integrator time constant by increasing the input resistor value because of the increased drift in output voltage which would occur. The integrator range is extended by switching additional capacitors in parallel. As an additional capacitor is switched in parallel the charge redistributes evenly amongst the capacitors. A comparator measures the integrator output voltage. When this exceeds a reference voltage the comparator output transition increments a chain of flip flops to switch in an additional capacitor. Hysteresis was included to avoid multiple output transitions from the comparator. In the prototype up to three additional capacitors can be switched in. The minimum capacitance is 100nF, this increases up to a maximum of 1.96μF. The autorange threshold was set at 3.89V, 95% of the ADC full scale. It was not found that the use of solid state switches to select additional capacitors introduced error due to charge injection or caused output drift because of leakage current.

5.2.5 Signal present indication

A comparator monitors the input to the interface unit to detect the presence of a valid optical signal. The comparator output is used by the microcontroller to determine the total on time during a measurement and to count the number of pulses. Initially a fixed threshold of approximately 20mV with 2mV hysteresis was used. This approach had
the disadvantage that the indicated pulse width was a function of the pulse amplitude and the pulse rise time. Subsequently the design was modified to obtain a reference voltage from the peak detector. The threshold for indicating signal present was set at half of the peak detector output voltage. A constant bias is applied to the comparator reference pin to ensure that the minimum threshold remains at 20mV. This avoids possible spurious comparator operation at the start of a measurement when the peak detector output is near zero. In the majority of cases the use of half the peak detector output as the threshold for signal present indication corresponds to the 50% points on a pulse train. The measured value of pulse width then corresponds to pulse duration $t_H$ as defined by ISO11145 [33] and used in BS EN 60825 [3].

5.2.6 Analogue to Digital conversion

A twelve bit ADC was used, the additional cost over an eight bit device was minimal and the increased dynamic range meant that fewer ranges were required in the detector head. The ADC device used (MAX187) has an internal 4.096V reference. This was buffered externally and used for the autorange and overload detection functions. An analogue multiplexer is used to select each of the three inputs in turn. In this application the extra time taken to perform these conversions sequentially is unimportant; the cost saving of using a single ADC was more significant.

The peak voltage and integrator output voltage are derived directly from the relevant circuits. Ambient temperature is measured using a dedicated device, an LM335 temperature sensor. Temperature compensation is required primarily to compensate for variations in detector responsivity. Measuring the temperature in the interface unit assumes that the whole instrument is at thermal equilibrium (as will usually be the case). This is not a significant disadvantage and avoids the overhead of fitting each detector head with a temperature sensor and interface electronics.

5.2.7 Overload detection

A circuit was required to operate independently of the peak detector and to indicate whether a detector overload had occurred. Overload conditions are detected by a fast comparator using positive feedback to give a latched output. Any input voltage
exceeding 8 V is regarded as an overload. In most cases this is a conservative limit, governed by the dynamic range available from the electronics rather than the detector. The comparator is reset before each measurement and the state of the output read after each measurement by the microcontroller.

5.3 DESIGN OF THE COMPUTER SOFTWARE

5.3.1 Introduction

A commercially available computer was used to perform the calculation and user interfacing functions of the instrument. There was no benefit in developing a computer specifically for the application. The choice of computer was governed by the need for portability, low cost, ease of software development and provision of a serial (RS232) port. A laptop computer was considered for the task. The primary disadvantages were high cost, limited battery life and excessive size. Palmtop computers were considered as an alternative. These have a more limited processing power than laptop computers but are considerably cheaper. A range of palmtop computers is available, of these the Psion Series 3a was selected. The main advantages were the high quality user interface, the relatively large memory available and the availability of a software development kit. Using the software development kit permitted the development of applications using the Psion graphical user interface (GUI) which addressed many of the requirements for a user interface.

The design of the software concentrated on two areas, the user interface and the underlying assessment process. Guidelines for the design of software based user interfaces were considered in the software design. The advantage of performing the assessment process in software with general purpose measurement hardware is demonstrated by considering the impact of proposed changes to the current standard.

5.3.2 Implementation of the user interface

The "eight golden rules" on the design of human-computer interfaces provided by Shneiderman [85] and described in Section 2.5.3 were applied in the software development. The benefit of using the Psion was apparent, many of the aspects of the
human-computer interface design are already addressed by the Psion operating system or simplified by functions available in the software development kit.

The software was written to provide control of the instrument functions from a menu structure. A range of typical functions are illustrated in the menu; file save and file open, measurement summary printing, test head and start measurement. All menu functions were associated with short cut key combinations to enable experienced users to progress rapidly through the initial stages. In the prototype only the measurement based functions were implemented. File and print based functions were only software based and as such provided no novelty in their implementation.

User dialogues were divided into three types (information, action and warning) and each identified with an appropriate header. Information dialogues provide the user with guidance about the measurement process, it was expected that experienced users would skip through these but they provide essential basic information for other users. Action dialogues are used when a specific action must be performed by the user as part of a measurement. Warning dialogues inform the user if a problem is encountered in the measurement. Some warning dialogues are combined with an audible warning to ensure the user's attention.

During the measurement a flashing message is displayed to remind the user that a measurement is in progress. This overcomes the lack of any response from the Psion until data is acquired and processed which could otherwise be mistaken for an error condition.

Where data is required from the user a message is displayed to explain what is required. In some cases a reasonable data value is suggested to guide the user, alternatively where a measurement is repeated the previous data remains displayed to avoid the need to repeat unnecessary data entry.

Error handling is inherent in the functions provided by the Psion software development kit. Most functions return error codes if unable to complete, the application was written to handle rather than ignore errors. The Psion operating system contains
functions for error message display, using these with appropriate explanatory text provided a suitable error handling method.

5.3.3 The measurement process

The three functions implemented in the menu were EXIT, TEST HEAD and MEASUREMENT. TEST HEAD performs a single measurement with the head gain set to maximum. The user is prompted to install the light shield over the detector before the measurement is made. If the output voltage from the head (which is proportional to the dark current) exceeds a threshold then this may indicate damage to the detector (Section 2.4.2.4). The user is then informed that the detector is damaged, otherwise they are advised to check for visible damage before continuing to use the detector. If a non photodiode detector head is fitted the user is warned (Warning Dialogue) that the test is inappropriate.

The main sections of the MEASUREMENT routine are illustrated in Figure 5.3. Significant user interaction is required to obtain measurement details and to provide guidance on the measurement process. From the user entry of wavelength an appropriate head and aperture are suggested (Information Dialogue). A reasonable value for the exposure duration is also suggested, this can be altered by the user if desired. During this section the serial port is opened and initialised. This automatically switches on the electronics in the interface unit. By opening the serial port at this point, the time taken for the user to select an exposure duration permits the electronics to stabilise before a measurement is made.

The user is requested to place the detector head in the measurement position (Action Dialogue), once the user indicates that this action has been performed the measurement starts. During the AUTORANGE function the gain is increased until sufficient signal is detected. If maximum gain is reached without significant signal, or a detector overload occurs, the function terminates and displays an appropriate warning message to the user (Warning Dialogue). On correct completion of the function the measurement data is transferred from the received data string into the appropriate variables. The user is requested to remove the detector from the laser radiation (Action Dialogue) and a background reading is taken. If the measured radiation does
Figure 5.3: The main software functions of a measurement
not significantly exceed the background, or if an inappropriate detector or aperture combination has been used the measurement terminates. A warning dialogue describing the cause of the error is displayed and the user returned to the menu. All the user entered data is retained to avoid the need to re-enter information. As each dialogue displays the previous user entered data is highlighted, if a change is required the new data automatically overwrites the old to save the user needing to delete old data first.

The HANDLE RESULTS function corrects for the characteristics of the detector and head gain by applying the inverse of the transfer function between optical radiation and ADC output. Each detector head has a specific function to generate values for the aperture area, responsivity and head gain. Aperture area is a constant value for each detector type. Responsivity is calculated for each detector using a polynomial approximation to the spectral response. Head gain is assigned a value according the start byte used for the measurement. If it is found that the detector head type and aperture diameter used are not the same as the ones recommended earlier in the process the user is notified (Warning Dialogue) and returned to the start of the measurement process. The previously entered data is displayed to save the user from having to repeat all the data entry. If the measurement has completed successfully the measured and background values are subtracted to give the true value of the laser radiation. This background subtraction function supplements the physical methods of background radiation rejection (limited detector spectral response and field of view). The final processing of the data and display of results depends on whether more than one pulse was counted. If so, the results are treated as a pulsed exposure, otherwise c.w. exposure is assumed.

For a pulsed assessment the total radiant exposure and pulse irradiance (or pulse energy if the pulse width is less than 18µs) of the measured radiation are determined from the integrator and peak detector outputs respectively. It is assumed that for all pulses with duration shorter than 18µs the peak detector output voltage corresponds to the maximum pulse energy. In the intermediate pulse width region (between 2µs and 10µs) this may cause the pulse energy to be underestimated. The total radiant exposure, as determined by the integrator output will still be measured correctly.
assessment for pulses shorter than 18μs is based on total energy and so no hazard is introduced, the only limitation is that the user may not be warned of a single more intense pulse if this only slightly exceeds the average value.

Where the pulse is relatively low, for example with high repetition rate pulse trains, the resolution of the hardware peak detector is limited. Under these conditions a value for pulse irradiance is derived from the total radiant exposure. Alternatively, if the total radiant exposure is relatively low, for example for a single short pulse, the pulse irradiance is used to determine the total radiant exposure. In effect, when one parameter has a limited signal to noise ratio the other is used to derive a value. Where both signal levels are low the integrator output is more reliable. This is because the integrator acts as a low pass filter and averages out the effect of white noise. The peak detector has no such bandwidth limitation, consequently noise will cause the actual signal to be overestimated.

A check is made that the total radiant exposure derived from the integrator output and from the product of pulse irradiance (derived from the peak detector) and total signal present time correlate. Where the pulse width is indicated as being less than 18μs, product of pulse energy (derived from the peak detector) and number of pulses is compared to the total radiant exposure from the integrator. If it is found that the measurements do not correlate then the implication is that there were spikes of more intense radiation, or other unusual features present. The user is warned about this, but since there is very little advice on hazard analysis of such waveforms in the Standards, no further information can be provided to the user.

If the measured radiation does not consist of a train of pulses the hazard assessment is regarded as a c.w. situation. A pulse train with very high (>56kHz) repetition rate is treated as a c.w exposure because the pulse stretching head causes the individual pulses to merge into a continuous signal. At pulse repetition rates in excess of 56kHz the MPE is determined by the average exposure condition, so no analysis of the pulses is required. The peak detector still provides the function of recording the presence of any individual pulses with greater than average energy.
A three stage approach was used to calculate the MPE. The first two stages locate the appropriate expression, the final stage uses the expression to determine the value of the MPE. Locating the expression uses two conditional levels. At each conditional level a variable is tested in turn against the subdivisions in the MPE tables until it is found to lie between two boundaries, at which point the correct section of the table has been located. Wavelength is used as the first variable because the wavelength subdivisions are constant across the table. A second set of conditions are then evaluated according to the exposure duration. A two stage process was essential because the boundaries of exposure duration are only constant within a wavelength region. From the second conditional layer a subroutine is called which performs the appropriate calculation of MPE.

For a c.w. case the MPE is calculated over the exposure duration selected by the user. Depending on the exposure duration the MPE in the standard [3] may be in units of radiant exposure or irradiance. In terms of hazard it is immaterial which units the results are presented in. Conceptually the c.w. case is associated with power or average power, therefore results are always presented as irradiance. The MPE value is converted if necessary. A summary of the measured and user entered data is presented. To provide an easily interpreted indication of the radiation hazard a bargraph is displayed along with a text message. The message indicates whether the MPE has been exceeded and is determined by the ratio of measured irradiance and MPE. A line is drawn at 75% of full scale to indicate the MPE irradiance. The measured value is scaled to display a bar terminating at the appropriate point. Figure 5.4 shows the final screen after a typical c.w. measurement. The indication of a "borderline" zone had not been implemented on the bargraph at this stage because the instrument accuracy was not fully determined.

A pulsed assessment is more complex, requiring that three aspects of the measured radiation be examined. These relate to average irradiance, single pulse radiant exposure and reduced single pulse radiant exposure. Two MPE values must be calculated; for the exposure duration and for a pulse duration. If certain conditions are fulfilled (as defined in the Standard [3] and described in Section 2.2.4) then the single pulse MPE is reduced to compensate for the cumulative effects of the pulse train. If
Figure 5.4: The computer screen after a c.w. measurement

Irradiance = 1.73E+11 Wm\(^{-2}\)
MPE = 2.55E+11 Wm\(^{-2}\)
Wavelength = 633 nm
Exposure Duration = 0.25 s
MPE NOT EXCEEDED

Figure 5.5: The computer screen after a pulsed measurement.

Pulse = 6.36E-12 Jm\(^{-2}\) Average = 5.71E+10 Wm\(^{-2}\)
Pulse MPE = 9.88E-12 Jm\(^{-2}\) Average MPE = 2.55E+11 Wm\(^{-2}\)
Wavelength = 633 nm
Exposure Duration = 0.25 s
Pulse Width = 2.61E-13
MPE NOT EXCEEDED
MPE NOT EXCEEDED

Figure 5.6: The prototype instrument
the pulse repetition rate is lower and pulses are resolved then the total number is multiplied by the exposure duration to extrapolate from the pulses counted during the one second measurement. To this result a final test is applied to avoid an over restrictive MPE being applied, again as defined in the Standard [3] and described in Section 2.2.4.

The average exposure measurement and MPE are expressed in units of irradiance in keeping with the c.w. philosophy. Pulse measurement and MPE are expressed in units of radiant exposure. This is in accordance with the use of energy to describe pulses. Presentation of results is similar to the c.w. case. Two columns are required to distinguish between pulse and average MPEs. Figure 5.5 shows the final screen after a typical pulsed radiation measurement.

The use of bargraphs facilitates a quick, qualitative assessment of the hazard which is useful during initial measurements and alignment of the detector head. Numerical values are displayed for the final quantitative assessment. This dual type of display matches the data presentation format to the two main tasks envisaged in Section 2.5.3.

The prototype instrument is shown in Figure 5.6. The silicon photodiode detector head is at the left of the photograph with the inlet aperture being visible. A precision aperture immediately behind the lens defined the 7mm measurement aperture. The interface unit is at the centre of the photograph, this contained a stack of two printed circuit boards, one performing the analogue signal processing and the other the digital interfacing. The batteries were also housed in this enclosure. The detector head and serial link plug in to the rear of the interface unit. To the right of the photograph is the Psion computer (showing the results of a pulsed assessment). The Psion serial interface is visible between the computer and the interface unit.

5.3.4 The benefits of a software based instrument

The advantage of performing the majority of task specific data processing in software can be demonstrated by considering one implication of a proposed change to the laser safety standard. This change was proposed by Schumeister [18] to improve and correct IEC825-1. One of the more significant proposals relates to the MPE
expression for infra red exposure between 2.6\mu m and 10^6\mu m and pulse widths between 1ns and 10s. It is stated that the present expression for the MPE (5600t^{0.25}Jm^{-2}) does not predict the damage potential of pulse trains well when multiplied by N^{-0.25}. As an alternative it is suggested that an MPE expression for the radiant exposure of (100+2150t^{12\text{TOT}}1^{16}Jm^{-2}) where t is the exposure duration and TOT is the total time during which the laser emits is better related to damage thresholds. Similar changes are proposed at visible wavelengths (where the single pulse MPE is at present proportional to t^{0.75}Jm^{-2}). It is noted that the current standard does not treat the effects of pulses of differing duration and maximum power satisfactorily. The proposed assessment method based on total energy and total on time would simplify the process. Schumeister does not explicitly consider the effect of a single more intense pulse in a train, the expressions assume only total exposure to be significant in determining hazard. It would probably be necessary to monitor for pulses having greater than average power or energy as at present.

To include this change to the standards would require the Psion software to be rewritten, but the changes would not be extensive. It would be necessary to verify that the measured radiant exposure did not exceed the permissible radiant exposure over the exposure duration and the total on time of the laser radiation. Only the functions concerned with MPE calculation and display of results would require modification. The measurement data acquired by the prototype is sufficiently generic to avoid the need to modify the hardware. Total on time is already measured, exposure duration is obtained from the user. Total radiant exposure is measured by the integrator. If the pulse train was composed of short pulses then the pulse stretching head (if used) would cause total on time to be overestimated. It would therefore be necessary to prompt the user for values of pulse repetition rate and width of short pulses. A pulse stretching head would still accurately determine the total energy. Many laser exposure conditions could be assessed without user intervention so long as the pulses were longer than the onset of pulse stretching and at a low enough repetition rate to be resolved.

A significant change to the standards could therefore be accommodated by changes only to the software running on the computer. The design philosophy of maintaining
generic instrument functions and task specific data processing software is vindicated by this. A hardware specific instrument would require complete redesign to achieve similar updating. This would be difficult and costly.

5.4 COMMERCIAL DEVELOPMENT OF THE MPE METER

Since the completion of the research project the prototype instrument has been developed into a commercial product in collaboration with a UK company. The modular strategy developed during the research project was applied to the commercial instrument. The hardware design developed for the prototype remained unmodified, it was only necessary to combine the two printed circuit boards into a single board. The commercial instrument supports the full range of detector heads. Initially the MPE meter is to be sold with the silicon photodiode detector head. InGaAs, thermopile and pyroelectric detector heads are being developed from the prototype designs.

The Psion software has been extended to include functions such as file storage and printing of results. Storage of the calibration factors in EEPROM devices is to be implemented. Calibration factors are stored locally in each detector head and the interface unit so that heads are interchangeable. The calibration factors compensate for the spectral dependency of detector responsivity and optical component transmission. Additional software modules are included on the Psion to use the calibration factors to calculate the measured irradiance or radiant exposure. The functions of MPE determination, calculation and display of results have been taken directly from those used in the prototype instrument. To a user the instrument software therefore appears identical to the prototype.

An external product design company was used to design an ergonomic case for the meter. Personnel from Loughborough University were closely involved in defining the user requirements and evaluating trial models. The interface unit has been designed to be "worn" using a shoulder strap to facilitate field use. A recess is moulded into the interface unit case to hold the Psion computer securely with the Psion serial link being housed within the interface unit case. It is possible to connect to a PC through the
interface unit so that measurement data stored on the Psion may be copied or imported into other applications. Detector heads are designed in two parts. The hand grip mates to the detector head electronics case through a multipole connector. This approach avoids the need for each detector head to have a cable attached which would otherwise make the storage of several heads cumbersome. Standard tripod mounts are provided in the handgrip for measurements where it is possible to fix the head in position.

An additional connector on the rear of the interface unit gives access to all the important signal and data lines. It is intended that this will enable additional functions to be developed for the commercial instrument, such as general purpose laboratory laser power and energy measurement.

The case design of the commercial instrument is shown on the following page.
A portable laser exposure meter providing simple assessment of laser safety. The LaserMPE provides accurate measurement of laser power for all hazard situations allowing the safety to be assessed to the appropriate standard.

- Easy to use
- Portable and compact
- Versatile yet affordable
The LaserMPE consists of a measurement head and a digital processing unit which automatically sets the appropriate parameters complying with the latest laser safety standards and graphically signals a pass/fail on the permitted exposure.

- Portable for field or laboratory use
- Lightweight and rugged
- Battery operated
- Measurements comply with BS EN 60825
- Measures CW and pulsed lasers
- Measurement heads for UV, visible and infrared
- Calibrated to traceable standards
- Processing by upgradeable software

### SPECIFICATIONS

<table>
<thead>
<tr>
<th>Weight:</th>
<th>1.0 kg</th>
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<tr>
<td>Power supply:</td>
<td>5 AA batteries</td>
</tr>
<tr>
<td>Processing:</td>
<td>Psion 3a computer</td>
</tr>
</tbody>
</table>

**VISIBLE MEASUREMENT HEAD**

- Detector: Si photodiode
- Sensitivity: 300mV over 7mm aperture
- Wavelength: 400-950nm
- Max power (no attenuator): 10mW

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Precision-Optical Engineering reserve the right to change the specifications contained in this leaflet.

Psion 3a is a trademark of Psion

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For further information about this product and applications, please contact our Sales Department.

PRECISION-OPTICAL ENGINEERING
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A business centre of British Aerospace Defence Ltd (Dynamics Division).
5.5 SUMMARY

The interface unit was designed to measure the appropriate parameters of the detector head output. This required the implementation of an auto-ranging integrator, a peak detector, a variable threshold signal present detector, an overload detector, temperature sensing and analogue to digital conversion. A microcontroller was used to transmit and receive data from the computer, to set the gain of the detector head, to read identification data from the detector head and to control the operation of the functions in the interface unit. The peak detector was based on a collection of designs, the final design being optimised for the specific requirements of this application. A design for the integrator was adopted which had the best combination of accuracy for fast input signals and minimum drift of output voltage.

The computer module was implemented on a Psion series 3a palmtop computer. This fulfilled the requirements of portability, cost and ease of usage. The design of the user interface was influenced by a set of guidelines for human-computer interaction. A user is led through the measurement process by a series of dialogues and prompts. The calculation functions were implemented in accordance with the MPE values contained in the standard.

The benefit of performing the majority of the task specific functions in software was illustrated by considering the changes which would be required to adapt to a proposed radical change to the calculation of MPEs.
6 

RESULTS AND ACCURACY CONSIDERATIONS

6.1 INTRODUCTION

A range of tests were required to evaluate the performance of the prototype instrument. Individual detector heads were tested using electrical signals to simulate the optical input. Optical inputs were then used to verify the overall performance of the detector heads. There were three principal benefits of investigating the detector head performance electrically before performing optical tests:

1. Testing the electrical performance of the detector head enabled the additional factors of optical to electrical conversion to be excluded. This made it possible to verify that the signal processing functions operated as intended.

2. It was more straightforward to generate a wide range of input conditions electronically than optically.

3. Direct electronic generation of input conditions eliminated the uncertainty of converting the electronic stimulus to an optical signal.

The thermopile detector head was an exception to the procedure described above. Optical tests were used to investigate the detector output characteristics and then the same optical inputs were used to verify the characteristics of the detector head. It was feasible to use only optical signals because the tests were only required at low frequencies.

An investigation into the noise performance of the practical photodiode head was also performed.

The interface unit was tested using electrical inputs to verify the operation of the integrator, peak detector, signal present detector and overload detector.

Once the modules had been tested the performance of the entire instrument, including the Psion software was tested. This work concentrated on determining the measurement precision which could be obtained using the instrument. The predominant sources of precision errors in the prototype instrument are discussed.
Techniques for calibration are described, followed by a discussion of the systematic errors which could remain after calibration.

6.2 TESTING OF THE DETECTOR HEADS

6.2.1 Silicon photodiode detector head

6.2.1.1 Investigation of noise performance

The noise performance of the prototype photodiode head which included the pulse stretching function was compared to a basic transimpedance amplifier. Computer simulation of the circuit using PSpice during the design stages (Section 4.2.7) showed that the output signal to noise ratio increased at higher transimpedance gains. It was also found that the noise generated by the pulse stretching circuit was less than the noise which would be generated by a transimpedance amplifier designed to resolve short pulses.

Tests were performed using practical implementations of a transimpedance amplifier and the pulse stretching interface. The effect of varying transimpedance gain on the output noise voltage was investigated. Two alternative operational amplifier devices were used at each gain to determine the relative significance of voltage and current noise. For each circuit an OPA602 was used as the voltage amplifier, and either an OPA602 or LT1028 for the transimpedance/pulse stretching stage. The transimpedance/pulse stretching stage was operated with and without additional feedback capacitance to limit the signal bandwidth. The value was calculated to give a bandwidth of approximately 70kHz. A voltage amplifier followed the transimpedance/pulse stretching stage. This had a gain of 46.6 and a first order roll off of gain above 88kHz.

The output noise was measured using an oscilloscope with 20MHz bandwidth. It was found that connecting the photodiode (S1223) at the detector head input made no difference to the voltage noise at the output. This implied that it was the operational amplifier noise which governed overall output noise. Table 6.1 contains the noise
voltage estimated for each combination of transimpedance gain, filter capacitor and operational amplifier.

<table>
<thead>
<tr>
<th>Transimpedance Gain</th>
<th>Filter capacitor</th>
<th>Pulse stretching head noise voltage (peak to peak)</th>
<th>Transimpedance head noise voltage (peak to peak)</th>
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</thead>
<tbody>
<tr>
<td>1000</td>
<td>Stray only</td>
<td>5mV</td>
<td>5mV</td>
</tr>
<tr>
<td>4700</td>
<td>Stray only</td>
<td>18mV</td>
<td>6mV</td>
</tr>
<tr>
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<td>470pF</td>
<td>13mV</td>
<td>4mV</td>
</tr>
<tr>
<td>82 000</td>
<td>Stray only</td>
<td>150mV</td>
<td>Oscillated</td>
</tr>
<tr>
<td>82 000</td>
<td>22pF</td>
<td>120mV</td>
<td>40mV</td>
</tr>
<tr>
<td>1000</td>
<td>Stray only</td>
<td>5mV</td>
<td>Oscillated</td>
</tr>
<tr>
<td>1000</td>
<td>470pF</td>
<td>2mV</td>
<td>2mV</td>
</tr>
<tr>
<td>4700</td>
<td>Stray only</td>
<td>5mV</td>
<td>5mV</td>
</tr>
<tr>
<td>4700</td>
<td>470pF</td>
<td>5mV</td>
<td>2mV</td>
</tr>
<tr>
<td>82 000</td>
<td>Stray only</td>
<td>60mV</td>
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</tr>
<tr>
<td>82 000</td>
<td>22pF</td>
<td>40mV</td>
<td>20mV</td>
</tr>
</tbody>
</table>

Table 6.1: Results of noise measurements on pulse stretching and transimpedance detector heads. (Operational amplifier OPA602 for \(^1\) and LT1028 for \(^2\))

The accuracy of the results for the LT1028 operational amplifier was less than for the OPA602 because the limited noise amplitude made it difficult to estimate from the oscilloscope. Despite this it was apparent that the LT1028 generated less output noise than the OPA602. The lower output noise of the LT1028 confirmed the importance of the operational amplifier and implied that minimising voltage noise is more important than minimising current noise. The OPA602 has a current noise of 0.6 fA/Hz\(^{0.5}\) and voltage noise of 13 nV/Hz\(^{0.5}\) and an LT1028 a current noise of 4.7 pA/Hz\(^{0.5}\) and voltage noise of 1 nV/Hz\(^{0.5}\).

A disadvantage of the LT1028 is that the bias current is significantly higher than that of the OPA602. Bias current results in an offset voltage at the output. The unipolar operation of the analogue to digital converter in the interface unit means that only positive offsets can be compensated for by the background subtraction function. Negative offsets will introduce a threshold below which the instrument will not respond to incident radiation. Consequently some form of bias cancellation or offset
nulling would be required, this would degrade the stability or noise of the circuit. It may therefore be preferable in practice to accept a higher noise output and use the OPA602 device to avoid offset problems.

It was found that the pulse stretching interface remained stable at each gain with only stray feedback capacitance. The transimpedance required feedback capacitance for stability. This was a benefit of the inductor isolating the photodiode capacitance from the amplifier. Limiting the bandwidth reduced the noise voltage for both the pulse stretching and transimpedance implementations.

The OPA602 device generated sufficient noise to permit comparison of the pulse stretching and transimpedance circuits. Approximately three times more noise was generated by the pulse stretching circuit than the basic transimpedance amplifier. The noise voltage increased more slowly than the gain increased, as predicted by simulation (Table 4.4). This confirmed the advantage of maximising the gain in the first stage rather than relying on subsequent voltage amplification. The factor of three increase in output noise compared to the transimpedance amplifier demonstrated the advantage of the pulse stretching design. Using the pulse stretching head permits correct measurement of pulses of nanosecond duration. If the standard transimpedance amplifier were to resolve similar pulse widths the bandwidth would need to be increased by a factor of at least 1000. Even if the faster operational amplifier had an equally good noise performance, the increase in bandwidth alone would be expected to increase the noise voltage by a factor of 32.

To place the experimentally determined values in context it is useful to consider the noise which would be generated by the feedback resistor of the transimpedance amplifier alone. At room temperature an 82kΩ resistor generates 364µV r.m.s. over a 100MHz bandwidth, this would be multiplied by 20 in the final amplifier to give 7.28mV. Peak to peak noise voltage is approximated as six times the r.m.s. value [93], hence the resistor noise over a 100MHz bandwidth alone would exceed the present pulse stretching head noise.
6.2.1.2 Tests using electrical inputs

Electrical inputs were used to directly investigate the behaviour of the prototype detector head circuit by excluding the effects of optical to electronic conversion in the photodiode. The photodiode window was covered with opaque material and current was injected across the device from a pulse generator in series with a 10kΩ resistor. The polarity of the output was inverted from normal because the pulse generator injected current whereas in normal operation photocurrent is drawn out of the virtual earth. Figure 6.1 shows the detector head output when the input was a train of 10ns pulses at 30kHz repetition rate. The transimpedance gain was $82 \times 10^3$ and the voltage gain was 20 (maximum head gain). The pulse stretching operation is apparent and the relatively low repetition rate ensures that individual pulses are resolved. Figure 6.2 shows the pulse stretching head output for a train of 1μs pulses at a frequency of 280kHz (transimpedance gain 4300, voltage gain unity). Individual pulses are no longer resolved and appear as ripple superimposed on the average value of the input signal. This demonstrates the response to high repetition rate pulse trains; the output corresponds to the average irradiance. A single pulse with greater than average energy would generate an output greater than the normal ripple amplitude which would be recorded by the peak detector in the interface unit. Figure 6.3 shows the output of the circuit when the input was a pulse train of approximately 18μs duration. The transimpedance gain was 4300 and the voltage gain unity. It is apparent that the head causes a slight reduction in rise time but provides an output proportional to the pulse power. For longer pulses the reduction in rise time becomes insignificant.

6.2.1.3 Tests using optical inputs

Final verification of the photodiode based head operation used optical inputs. The linear LED drive board described in Appendix 1 was used to generate similar optical pulses to those used in the electrical tests. It was found that the electrical and optical inputs produced equivalent pulse response outputs from the detector head. The response of the detector head to short optical pulses was investigated using a frequency doubled Nd:YAG (532nm) laser with a pulse width of approximately 20ns and repetition rate 50Hz. A ground glass transmissive diffuser was used to reduce the
Figure 6.1: Output of the silicon photodiode head for 10ns input pulses. CH1 (current input) 2V/div, CH2 (head output) 0.2V/div, X 10μs/div

Figure 6.2: Output of the silicon photodiode head for 1μs pulses at 280kHz. CH1 (current input), 5V/div, CH2 (head output) 0.5V/div, X 10μs/div

Figure 6.3: Output of the silicon photodiode head for 18μs pulses. CH1 (current input) 0.5V/div, CH2 (head output) 2V/div, X 20μs/div

Figure 6.4: Response of the silicon photodiode head to a 20ns optical pulse. 50mV/div, X 10μs/div
energy reaching the photodiode. Figure 6.4 shows the detector head output. The transimpedance gain was 200 and the voltage gain unity. Some ringing is apparent on the leading edge of the output pulse. This was present even with the detector blanked with opaque material and was attributed to pick up of radiated noise as the laser flashlamps fired.

6.2.2 Pyroelectric detector head

6.2.2.1 Tests using electrical inputs

The novel aspect of the pyroelectric detector head was the d.c. restoration. It was not practical or beneficial to investigate the d.c. restoration function by computer simulation. Testing of the actual circuit performance was more useful. Before electrical inputs could be used it was necessary to filter the signal to approximate to the thermal effects of the pyroelectric detector on the optical signal. The high pass filter shown in Figure 6.5 was used, R and C give an electrical time constant equivalent to the thermal time constant of the detector. Current is injected to the detector head input (virtual earth) through the 100kΩ resistor. A 100Ω resistor was required to prevent the capacitance of the oscilloscope probe degrading the operational amplifier stability.

Figure 6.5 : Circuit used to simulate the thermal behaviour of the pyroelectric detector.

Figure 6.6 shows the filter output modelling the detector approaching thermal equilibrium after the start of an optical pulse train (10ms duration pulses at 25Hz repetition rate). The output from the detector head is maintained as a unipolar signal with constant zero level despite the changes to the input signal baseline. The detector head transimpedance was 200. Figure 6.7 shows the output of the detector head for a square wave input at the minimum pulse repetition rate (20Hz). A detector head
transimpedance of 200 was used. Some distortion of the pulses is apparent but the d.c. restoration operates as required. At the other extreme of operation Figures 6.8 and 6.9 show the output of the detector head with input pulses 50µs in duration but with differing pulse repetition rates. The signal generator output voltage was reduced for these pulses and the detector head transimpedance gain increased to $77.8 \times 10^3 \text{VA}^{-1}$ so that the amplifier speed could be verified. It is apparent that the d.c. restoration circuit corrected the changes in the input baseline as the pulse train duty cycle changed. The bandwidth of the circuit was sufficient to resolve 50µs pulses, even at this highest transimpedance gain.

6.2.2.2 Tests using optical inputs

Optical tests of the detector head used a variable speed rotary chopper and a c.w. argon ion laser (532nm) to provide pulse trains of known pulse power, width and repetition rate. Figure 6.10 shows one an example of the results. The detector head transimpedance was $1.5 \times 10^6 \text{VA}^{-1}$ and the incident pulse power was 350mW. The detector head output voltage was measured at the interface unit input. At this point the resistors used to terminate the cable between the head and interface unit introduced an attenuation factor of 2. The actual detector head output voltage was therefore twice the voltage shown in Figure 6.10. Noise is apparent on the output. The low frequency ripple could be removed by more thorough detector shielding and was a result of pickup at the transimpedance amplifier input. The broadband, white noise is of a lower amplitude, approximately 5mV peak to peak. This noise is approximately equivalent to 15mW peak to peak variation of incident power and would only start to be significant for the lowest MPE pulse power encountered (40mW pulse power).

A specific verification of the linearity of the pyroelectric detector head was performed. This was unnecessary for the photodiode and thermopile detector heads because the circuit transfer function was linear by nature. It was not possible to make this assumption with the pyroelectric detector head because of the effect of the offset removal function. Detector head linearity was investigated over the pulse power range 100mW to 500mW (the upper limit being governed by the available laser power) using the rotary chopper and argon ion laser. A constant pulse width of 20ms at
approximately 25Hz was used, the laser power was then adjusted using the "light control" on the laser. A Coherent LM10 thermopile head was used to measure the c.w. laser power before the chopper. Figure 6.11 shows the detector output at various pulse powers and a best fit straight line (correlation coefficient \( r = 0.998 \)). The voltages measured have been multiplied by two to allow for the attenuation caused by measuring at the interface unit input. The gradient of the line of best fit is 0.488 V/W, the transimpedance was \( 1.525 \times 10^6 \) VA, implying a detector responsivity of \( 0.32 \mu \text{A W}^{-1} \). This is 2.5 times lower than the minimum value given in the manufacturer's specifications (0.8\( \mu \text{A W}^{-1} \)). Some of this may arise from reflection and
absorption losses through the detector window combined with a lower detector absorption coefficient at visible wavelengths.

Figure 6.10: Output of the pyroelectric detector head to an optical pulse train. 20mV/div, X 10ms/div

Figure 6.11: Pyroelectric detector head response to varying optical pulse power.
6.2.3 Thermopile detector head

6.2.3.1 Tests using optical inputs

The frequency response of the detector head filter had been simulated during the design process to verify that the calculated component values gave the required frequency and pulse response. Modelling the detector behaviour electrically was unnecessary. The high responsivity of the thermopile and low frequency of operation made it practical to use optical inputs directly. Suitable optical pulses were generated using the single LED drive board described in Appendix 2.

Measurements were made of the detector head output voltage with and without frequency compensation. Where appropriate the frequency compensation was disabled by removing C1 and C2 (Figure 4.27). Figure 6.12 shows the output of the uncompensated detector head for an optical input of 100ms pulses. For comparison Figure 6.13 shows the output of the detector head with the same optical input when frequency compensation was used. The output pulse has been reconstructed successfully. Using 20ms optical pulses the rise time was measured as approximately 5ms. This will permit satisfactory operation with 50ms pulses. Negligible noise was apparent, despite the increased gain at high frequencies.

![Figure 6.12: Response of the thermopile detector to optical pulses without frequency compensation. CH1 (optical input) 2V/div, CH2 (amplified thermopile output) 0.2V/div X 20ms/div](image1)

![Figure 6.13: Response of the thermopile detector to optical pulses with frequency compensation. CH1 (optical input) 2V/div, CH2 (compensated thermopile output) 0.2V/div X 20ms/div](image2)
6.3 TESTS OF THE INTERFACE UNIT

The operation of the peak detector was verified by injecting single voltage pulses directly into the interface unit input. It was found that the peak detector was capable of capturing the peak value of a single pulse to within 5% for any pulse longer than 5μs. Subsequent pulses of the same amplitude and width caused the peak detector output to increase to the true pulse amplitude. The overload detector was found to respond to a single 8.20V pulse (overload detector threshold 8.192V) for all widths greater than 1μs, ensuring that any overload conditions would be detected.

To verify the linearity of the interface unit it was necessary to use a detector head so that the automatic range functions were operative. If the input was applied directly to the interface unit the range of permissible input voltages was restricted. Below a threshold (200mV) the instrument repeatedly attempted to increase the range to increase the reading. Without a detector head attached the gain did not increase, the interface unit received a constant input voltage, consequently the measurement process terminated with a warning that insufficient radiation was present. The silicon photodiode head was used because it was the most thoroughly tested and characterised. Current was injected across the photodiode (with polarity such that current was drawn out of the photodiode virtual earth to provide the correct output signal polarity). An external variable voltage source in series with a 33kΩ resistor was used to generate the input current which was proportional to the injected current. A range of currents were applied to emulate a range of typical irradiances. Figure 6.14 shows the results, the applied current was plotted against the irradiance displayed by the computer (wavelength was set to 633nm). The effect of the range change is visible around 200μA input current where there is a slight discontinuity in the transfer function. This would be corrected during full calibration of the instrument. Linearity is excellent, the straight line fitted to the data points had a correlation coefficient $r = 0.9998$. 

181
Figure 6.14: Displayed irradiance versus current injected into silicon detector head.
6.4 DETERMINATION OF THE INSTRUMENT PRECISION

6.4.1 Terminology

Figure 6.15 shows the inter-relation of the terminology used in this work to describe the instrument error analysis. This is based on the information and definitions provided by Wheeler and Ganji [106].

![Diagram of terminology inter-relation]

An instrument for laser radiation hazard assessments performs a safety critical function. It is therefore essential that the measurement results are accurate and that the measurement error is quantified. Measurement error is composed of a systematic error and a precision error [106]. The uncertainty of a measurement is defined as an estimation of the measurement error based on a set of repeated or replicated measurements [106]. For a complex instrument such as this one it is preferable to estimate the measurement error as an uncertainty. Deriving instrument accuracy from a full error analysis of the elemental error sources risks neglecting error sources. Estimating error on the basis of a determination of measurement uncertainty does not have this limitation.

The precision error is determined from the sample standard deviation of the measured values for each measurement condition. This defines the "precision index" [106]. The "precision limit" for a single measurement is estimated by multiplying the precision
index by the value of Student's $t$ statistic at the chosen confidence level (95% throughout this work) and appropriate number of degrees of freedom.

Systematic errors may be addressed by a calibration procedure in which the difference between a known input and the measured value is used to calculate a correction or calibration factor. Once the calibration factor has been determined it may be used in subsequent measurements to minimise the systematic error. After calibration the remaining systematic error is a function of the accuracy of the calibration process. The precision error cannot be removed by a calibration process.

6.4.2 Introduction

The evaluation of the prototype instrument performance concentrated on estimating the precision errors. No attempt was made to estimate the systematic errors. This was in recognition of the fact that the measurement error is determined by the combination of systematic and precision errors and therefore can only be evaluated when the instrument has been fully calibrated. Given that the systematic errors could be reduced to any level required, subject to the availability of suitably accurate standards, the most useful indicator of instrument performance is the measurement precision. An instrument which is not precise can never be accurate, precision is a prerequisite of accuracy. A precise instrument may be made accurate by using a suitable calibration procedure. The precision of a measurement obtained from an instrument may be regarded as an indication of the quality of that instrument.

In the instrument it would be preferable to reduce systematic errors to be insignificant in comparison to precision errors. This is because it is possible to reduce the precision error in the estimation of the true value by making multiple measurements. There is no similar method for reducing the systematic error in a measurement. The estimated measurement uncertainty would be displayed after each measurement as a "borderline" region on the bargraph indicating the proximity of the measured value to the MPE. A measurement of radiation falling in this region might or might not exceed the MPE. Multiple measurements, or a more accurate instrument would be required to determine the actual hazard. Given that the MPE does not represent an absolute division between hazardous and non-hazardous radiation [3] it would be preferable to regard
radiation in the borderline region as being unsafe. If the systematic errors in the measurement were significant then it would be necessary to make an additional allowance in the borderline region.

Optical inputs were used for the instrument evaluation. These were generated by an LED or a scanned laser beam. The silicon photodiode detector head was used. This permitted operation over a wide range of pulse widths and repetition rates. An additional advantage was that visible sources could be used which facilitated alignment of the detector and source. The incoherent radiation generated by the LEDs was not expected to affect the validity of applying the results to the measurement of coherent (laser) radiation.

All the tests were performed over a short time duration. The determination of precision was therefore based on repeatability rather than reproducibility. This does not fully estimate the precision because the effect of long term variations caused by changes in the measurement environment (for example ambient temperature, humidity) are excluded. It was necessary to take this approach because the optical sources and measurement equipment could only be relied upon to remain consistent over the short term. Attempting to record the measurement reproducibility could therefore not exclude the effect of source instability. The majority of elemental precision errors are effective in the short term and therefore measurement repeatability is capable of indicating the majority of measurement uncertainty.

The LED source represented the most controllable and precise optical pulse source. Tests performed using the scanned laser were less precise but were more representative of the intended operating conditions for the instrument.
6.4.3 Tests using LEDs

The linear LED drive circuit described in Appendix 1 was used for the tests. The following aspects of instrument operation were investigated:

- The precision of average irradiance measurements over a range of pulse repetition rates (between 33Hz and 10kHz) and four discrete duty cycles. The average irradiance was constant for each duty cycle.
- The precision of pulse energy measurement over the same range of pulse repetition rates and duty cycles. The pulse energy (and width) decreased with increasing repetition rate.
- The precision of pulse energy, average irradiance and pulse width measurement for a constant pulse width (nominally 50µs) and varying repetition rates. The pulse energy and pulse width remained constant whilst the average irradiance increased with increasing repetition rate.

Fundamental to the precision of each test was the repeatability of the integrator (measurement of average irradiance) and the peak detector (measurement of pulse power).

The input signal for the LED drive board was taken from a pulse generator. An oscilloscope and frequency counter were used to monitor the pulse generator output. Ten sequential measurements were made with the instrument for each input signal. The interval between each measurement was approximately five seconds. The mean and standard deviation of each group of measurements were determined. From the standard deviation the precision limit for a single measurement was estimated at 95% confidence level and 9 degrees of freedom. The use of the LED source restricted the irradiance and pulse radiant exposure which could be generated. This was not a disadvantage because the worst case precision errors were expected to be at low irradiances and radiant exposures where elemental error sources such as noise, EMI and charge injection were most significant.

Figure 6.16 shows the precision of displayed average irradiance during the first test. The input voltage to the LED drive board was adjusted to give a measured irradiance of 5Wm\(^{-2}\) for a square wave input (50% duty cycle). Under these conditions an LED
drive board input voltage of 0.8V was required. Red LEDs were used and the wavelength entered on the Psion was 633nm. Error bars show the standard deviation for each measurement result. It is apparent that the measurement precision was excellent. The largest single precision index (standard deviation) was $0.377\text{Wm}^{-2}$ for the 80% duty cycle, 100Hz measurement. Using Student's $t$ distribution for a confidence level of 95% and 9 degrees of freedom gives a value of $t = 2.26$. The precision limit (uncertainty) for each measurement was therefore $\pm 0.852 \text{Wm}^{-2}$, $\pm 1\%$ of the sample mean. The displayed irradiance was found to be largely independent of pulse repetition rate at each duty cycle.

Each time the pulse repetition frequency was altered it was necessary to re-adjust the pulse train duty cycle. The duty cycle could only be determined from the oscilloscope display which was a subjective measurement. This subjectivity accounts for the change of displayed average irradiance between 100Hz and 1kHz at 80% duty cycle. This factor may also have affected the measurement at 100kHz and 10% duty cycle. An additional contribution to the increase of displayed average irradiance was the short width of the on pulse (1μs) and finite response time of the LED and drive board. The LED drive was single ended, this ensured rapid turn on of the LED, but at turn off the LED was left floating. All charge carriers in the device remained to recombine and emit light rather than being extracted. This introduced a short tail to the optical pulse which became a significant proportion of the energy of short pulses. The uncertainty in the pulse duty cycle makes the variation of displayed irradiance with pulse repetition rate unreliable as an indicator of the instrument precision. The results shown in Figure 6.18 and discussed later are a more appropriate indicator of this aspect of instrument precision.

Figure 6.17 shows the precision of displayed pulse radiant exposure during the second test. For each duty cycle a tenfold increase in repetition rate resulted in a tenfold decrease in pulse energy. This is the result of maintaining a constant duty cycle with increasing repetition rate; the pulse width must decrease by the same factor as the increase in repetition rate. Since the pulse power was constant this caused an equal decrease in pulse energy.
At the highest pulse repetition rates and 16.7% duty cycle the pulse energy is greater than expected. The pulse width was 5μs, the optical tail from the LEDs would only account for a minor increase in pulse energy. The majority of the increase in displayed energy arose because the Psion software was using the peak detector head output voltage as a measure of pulse irradiance, but assuming a pulse duration of 18μs. For a 5μs pulse the detector head peak output voltage is in the intermediate region between being proportional to pulse irradiance and to pulse energy (Figure 6.2, Section 6.2.1.3). The overestimate of pulse energy is only significant between 2μs and 10μs. A least squares linear fit to each set of data showed close correlation. The 16.7% duty cycle results showed the poorest correlation ($r = 0.9972$) as expected. All the other results had $r > 0.999$. For the worst case where only three data points were available (80% and 10% duty cycles), the correlation coefficient must be greater than 0.997 to be significant at the 95% confidence level [106]. It is therefore improbable that this correlation is due to chance.

Figure 6.18 shows the precision of the measured pulse radiant exposure, pulse width and average irradiance from the third set of tests. The pulse width was set on the pulse generator at 50μs and remained constant throughout the tests. It is apparent that the measurement of pulse width was consistent at each repetition rate and between repetition rates, the range between maximum and minimum values was less than 0.2% of the average value.
The constant pulse width and constant pulse irradiance generated by the LEDs implies that the measurement of pulse radiant exposure should remain constant over the range of pulse repetition rates. This was found to be the case. Over the full range of pulse repetition rates the range between maximum and minimum measured values of pulse radiant exposure was less than 1% of the overall average pulse radiant exposure. The greatest precision error was at 6644Hz where the average pulse radiant exposure was 5.38Jm⁻². The precision index of this set of measurements was found to be 0.0404Jm⁻². Using Student's \( t \) distribution for a confidence level of 95% and 9 degrees of freedom this corresponds to a precision limit for each measurement of ±0.0913Jm⁻², ±1.7% of the average value of pulse radiant exposure.

The constant pulse radiant exposure with varying pulse repetition rate implies that average irradiance must increase with repetition rate. Average irradiance was found to be directly proportional to repetition rate as expected. The correlation coefficient \((r)\) to a straight line was 0.9999. For eight samples the correlation coefficient must be greater than 0.834 to be significant at the 99% confidence level [106]. It is therefore improbable that this correlation is due to chance. The greatest precision error of an individual measurement was for an average irradiance of 2.55Wm⁻² (4895Hz). At this point the precision index was 0.0063Wm⁻². Using Student's \( t \) distribution a confidence level of 95% and 9 degrees of freedom corresponds to a precision limit for each measurement of ±0.014Wm⁻², ±0.56% of the average value of average irradiance.
Table 6.2 summarises the instrument precision determined by the tests using the LED source.

<table>
<thead>
<tr>
<th>Test details</th>
<th>Figure</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average irradiance, variable duty cycle and repetition rates.</td>
<td>6.16</td>
<td>Worst case Precision Limit ±1% of sample mean.</td>
</tr>
<tr>
<td>Pulse radiant exposure versus repetition rate with constant pulse irradiance.</td>
<td>6.17</td>
<td>Measured relationship correlated to expected with ( r \approx 0.9972 ).</td>
</tr>
<tr>
<td>Pulse width constant with variable repetition rate.</td>
<td>6.18</td>
<td>Difference between maximum and minimum pulse width &lt;0.2% of the average.</td>
</tr>
<tr>
<td>Constant pulse radiant exposure, variable repetition rate.</td>
<td>6.18</td>
<td>Difference between maximum and minimum pulse radiant exposure &lt;1% of the average. Worst case Precision Limit ±1.7% of average.</td>
</tr>
<tr>
<td>Average irradiance versus repetition rate, constant pulse radiant exposure.</td>
<td>6.18</td>
<td>Measured relationship correlated to expected with ( r = 0.999 ).</td>
</tr>
</tbody>
</table>

Table 6.2 : Summary of the instrument performance evaluated using LEDs.

The tests using the LED source indicated that the instrument had a high degree of precision. For comparison it should be noted that transfer standard photodiodes used by the National Physical Laboratory have 2\( \sigma \) uncertainties in the range ±0.1\% to ±1\% [107]. Although much more accurate standards are available (the Cryogenic Radiometer which forms the primary standard has a 2\( \sigma \) uncertainty of ±0.008% [107]) the performance obtained from the instrument is appropriate for the calibration standards available. Calibration to compensate for systematic errors accurate to 0.1\% would ensure that the precision dominated the overall instrument accuracy as required.

It is appropriate to compare the measurement precision estimate from the preceding tests with the requirements given by BS EN 61040:1992 [30]. It will be assumed that the source contributed negligible precision errors to the measurements. BS EN 61040:1992 [30] was described in Section 2.3.2. This document specifies minimum requirements for aspects of instrument accuracy and subdivides instruments into
classes on the basis of measurement uncertainty. At the design stage the aim was to meet or exceed the requirements of Class 10.

The majority of error sources described in the standard are controlled by the detector performance and external optical components. Non-linearity, errors of averaging repetitively pulsed radiation and zero drift are influenced by the hardware used to process the detector output signal. It was shown in Section 7.3 that the silicon detector head and interface unit was linear over the intended range of photocurrents.

The optical tests estimated the precision of average irradiance measurement (averaging with respect to time of repetitively pulsed radiation) to be ±1%, better than the typical ±2.5% which could be expected from a Class 10 instrument. Zero drift errors are made irrelevant by a background subtraction function as part of each measurement. BS EN 61040:1992 has no specifications for the precision with which individual pulse energy is measured, but the precision of approximately ±1.7% is in keeping with the requirements of a Class 10 instrument.

6.4.4 Sources of precision error

The most significant sources of the precision error were anticipated to be:

- Noise - externally induced (EMI) and internally generated.
- Charge injection to the integrator as solid state switches change state.
- Drift in the peak detector and integrator output associated with leakage through the solid state switches.
- Spatial variations of detector responsivity.

The magnitude of electronic noise was minimised by limiting the electronic bandwidth. In measurements where noise is significant the data with the greatest signal to noise ratio is used to calculate the results. The integrator has an inherent low pass filtering action which tends to average out white noise. The maximum values recorded on the peak detector will be more susceptible to noise, by the nature of the circuit operation the maximum value of signal plus noise is measured. A measurement of total radiant exposure will therefore be less affected by noise than the measurement of peak power (or energy). Susceptibility of the instrument to externally induced EMI was minimised.
by keeping the detector and first stage of amplification in proximity. Further improvements could be obtained by screening the detector heads.

The solid state switches introduce measurement uncertainty in the form of charge injection during a transition of state. The magnitude of charge injection is not constant between operations therefore the precision is affected. To a lesser extent the charge leakage may vary between measurements. Calibration removes the systematic error associated with the solid state switch effects and greatly reduces the measurement error which would otherwise occur. The background subtraction function is also useful in reducing the significance of solid state switch effects. For the prototype DG412 solid state switches were used and found to be satisfactory. The higher performance device, a MAX313 would be required when operation over a wide temperature range was necessary.

Variations in the responsivity over the detector reduce the measurement precision by introducing a dependency of the measured value on the incident beam position. This combines with the random nature of laser beam pointing stability drift and the positional instability associated with the hand-held detector head to reduce the instrument precision. Spatial non-uniformity was not expected to be significant for the photodiode detector. Manufacturer's data claims variations of less than 1%. This has been confirmed by Schaefer and Geist for one commercially available device [91]. No evidence was available that pyroelectric detectors would suffer spatial non-uniformity. This was not the case with thermopiles, earlier work revealed significant spatial non-uniformity (Section 5.4.5). In a final instrument it would be necessary to design the optical system to spatially average the incident radiation over the thermopile detector. Boivin [97] showed that optical interference effects associated with the detector window can significantly degrade the spatial uniformity of a detector. A wedged window or diffuser eliminates the problem.

6.4.5 Tests using a rotary laser scanner

The performance of the prototype instrument was investigated using scanned laser beams under controlled conditions. These tests demonstrated the measurement precision which could be expected in typical measurement applications. The
measurement results indicate the combined effects of precision error in the source and the instrument.

The rotary laser scanner was of basic construction; a bevelled mirror mounted on a motor spindle. This generated a circular pattern from the reflection of an off-axis laser beam. The scan rate of the pattern was proportional to the speed of the motor, but not necessarily to the voltage applied to the motor. Two motors and mirrors were provided in the scanner, with both running a variety of Lissajous figures could be generated by altering the motor supply voltages. For the test only one motor was powered and a circular scan was generated. A helium-neon laser was used. Before the tests the laser was left for thirty minutes to reach thermal equilibrium, thereby removing any errors caused by variations in the output power. The laser power after thirty minutes was measured as 1.92mW at the output of the laser scanner.

A lens and 7mm diameter aperture were fitted to the silicon photodiode head. The detector head was placed approximately 140mm from the scanner unit. At this point the scanned circle had a diameter of 35mm. Five different motor drive voltages were used, at each voltage ten measurements were performed, the interval between measurements being approximately five seconds. Figure 6.19 contains the results, the measured values of pulse radiant exposure and average irradiance are plotted for each measured value of pulse width. Error bars show the standard deviation for each set of measurements. The pulse width displayed by the Psion was used for the x axis in preference to motor drive voltage because of the unknown relationship between the motor drive voltage and rotation speed. Pulse width measurements had already been found to have high precision.

The measured value of average irradiance was expected to remain constant independent of the pulse width because the duty cycle of the pulse train was a function of the detector aperture diameter and scanned circle circumference, both of which were independent of the motor rotational velocity. A significant deviation from the constant value was observed at the longest pulse width. This deviation was caused by variations in the number of optical pulses received during the one second measurement period. At low motor speeds (16Hz for the longest pulse duration) the number of
optical pulses incident on the detector was small. The number received during a given one second period therefore varied between measurements. This did not affect the measurement of pulse width because the total on time and number of pulses decreased or increased together. Pulse energy measurement was unaffected since it was derived from measurement of the maximum pulse power and pulse width independent of the number of pulses. Only the average irradiance which was derived from the measurement of total energy (radiant exposure) over the measurement period was affected.

Excluding the measurement at the longest pulse width the range between maximum and minimum measured values of the average irradiance was 3.3% of the overall average value. For the worst case single measurement (1.47ms pulse width) where the average irradiance was 2.38Wm$^2$, the precision index was 0.025Wm$^2$. Using Student's $t$ distribution for a confidence level of 95% and 9 degrees of freedom this corresponds to a precision limit for each measurement of ±0.057Wm$^2$, ±2.4% of the overall average value of average irradiance.

The constant pulse power and duty cycle determined by the ratio of detector aperture to scan circumference implies that the pulse radiant exposure should be linearly proportional to the pulse width. It was found (Figure 6.19) that the pulse radiant exposure
exposure increased linearly with increasing pulse width (correlation coefficient $r > 0.9999$). This was as expected for a pulse train with constant pulse irradiance.

For the worst case single measurement (0.39ms) where the average pulse radiant exposure was $0.019\text{Jm}^{-2}$, the precision index was found to be $0.00011\text{m}^{-2}$. Using Student's $t$ distribution for a confidence level of 95% and 9 degrees of freedom this corresponds to a precision limit for each measurement of $\pm 0.000025\text{Jm}^{-2}$, $\pm 1.3\%$ of the average value of pulse radiant exposure.

Excluding the errors resulting from the variation in the number of pulses included in a measurement, the estimation of precision errors using the rotary scanner was similar to the results using the LED source.

6.4.6 Tests using a display laser system

The second scanned laser source was a computer controlled display laser system of the type which would be used for entertainment purposes in nightclubs and other venues. The performance of the same system has been analysed in Section 3.2.2.3. A circular scan was collapsed into a horizontal line, similar to the one shown in Figure 3.3. The flat pattern was moved over the detector head which remained fixed throughout the test. No lens was fitted to the photodiode, the beam scanned directly over the 1.1mm square sensitive area. Measured values of pulse width, pulse radiant exposure and average irradiance were all reduced as a consequence. A multi-line argon ion laser was used as the laser source. A wavelength of 500nm was entered on the Psion to represent the spectral average of the radiation. The actual value was unimportant, it was only important that the value remained constant for all measurements. At the measurement position (4.94m from the scanner) the beam diameter was approximately 5mm. The laser power after the scanner was 6.48mW (measured using a Coherent FieldMaster with LM2 head and assuming a wavelength of 500nm).

Three measurement positions along the scan were used. At each position ten measurements were made at intervals of approximately five seconds. The standard deviation of each set of ten measurements was used to construct error bars. The origin for the measurements was the end of the scan furthest from the multiple scans (see
Figure 3.3), the scan was 47.5 cm long at the measurement position. The three measurement positions were chosen to represent the three significant laser beam velocity regimes in the scan; stationary at the end, accelerating, and constant velocity close to the centre. Table 6.3 contains the measured values of pulse radiant exposure, average irradiance and pulse width and the calculated precision index and precision limit as a percentage of the measured value at each measurement position. The precision limit for each measurement was derived from the precision index using Student's t distribution with a confidence level of 95% and 9 degrees of freedom ($t = 2.26$).

<table>
<thead>
<tr>
<th>Displayed parameter</th>
<th>Measurement position (cm from end)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Pulse radiant exposure ($J/m^2$)</td>
<td>2.92</td>
</tr>
<tr>
<td>Precision index ($J/m^2$)</td>
<td>0.0523</td>
</tr>
<tr>
<td>Precision limit as a percentage of the measurement.</td>
<td>4.0</td>
</tr>
<tr>
<td>Average irradiance ($W/m^2$)</td>
<td>0.72</td>
</tr>
<tr>
<td>Precision Index ($W/m^2$)</td>
<td>0.008</td>
</tr>
<tr>
<td>Precision limit as a percentage of the measurement.</td>
<td>2.5</td>
</tr>
<tr>
<td>Pulse width (μs)</td>
<td>80.3</td>
</tr>
<tr>
<td>Precision Index (μs)</td>
<td>1.25</td>
</tr>
<tr>
<td>Precision limit as a percentage of the measurement.</td>
<td>3.6</td>
</tr>
</tbody>
</table>

Table 6.3: Results of the instrument test on a display laser system.

Pulse width was a maximum at the end of the scan where the beam came momentarily to rest. Moving away from the end of the scan the pulse width decreased as the single pulse resolved into two and the beam accelerated. This behaviour is evident in an abrupt decrease in all parameters away from the end of the scan. At 18.8 cm the beam velocity was at a maximum, the pulse width was less than 18 μs and was not displayed by the instrument because the pulse width was no longer significant for hazard evaluation.

It is apparent that the instrument measurements were less consistent than in the previous tests. This was not due to variations in laser power (which had been found to
be negligible when measured). The reduction in precision was attributed to positional instability in the scanner. Small shifts in the vertical position of the scanned pattern significantly affected the magnitude of the radiation received by the detector because of the small detector size and the non-uniform beam spatial power distribution. A small shift in the beam position changes the section of the beam sampled by the detector and causes a change in the irradiance measured by the detector. The change in the beam position at the detector could have originated in drift of the scanner drive electronics (causing a change in the angle of the laser beam) or in the relative position of the detector and laser scanner (which were mounted on separate benches). If the beam was averaged over a 7mm diameter aperture then this problem would be greatly reduced for beams with diameter less than 7mm.

The reduced measurement precision observed with the display laser system was a consequence of limited source stability rather than the instrument. Actual instrument measurement precision was best determined from the tests with LED sources. It is clear from this that the instrument measurement precision is sufficient for the application, it is desirable that the final system performance is limited only by the source characteristics.
6.5 CALIBRATION TECHNIQUES

6.5.1 Introduction

The fundamental purpose of the instrument was to transduce optical radiation to an electrical signal, convert this into digital data and display a numerical value in an appropriate format for laser radiation hazard assessment. Calibration is required to compensate for variations between individual instruments in the optical detection and the processing of the analogue signal. The calibration process reduces the variation between instruments to an acceptable level. Calibration contributes to measurement accuracy by reducing the systematic errors. It is important that the instrument design permits simple and comprehensive calibration so that systematic errors may be made insignificant in comparison to precision errors.

The responsivity of the detector may differ from the assumed value in magnitude or in relative spectral responsivity. Variations in magnitude were removed in the prototype by a basic calibration process in which head gain was trimmed for correct measured irradiance at a single wavelength. Sufficient adjustment range was included to allow for the typical batch to batch variations of ±25% [46] associated with photodiodes. Similar variations in responsivity are claimed by the manufacturers of the pyroelectric detector [72] and thermopile detector [79]. In cases where solid state switch resistance formed a significant part of a gain setting resistor, adjustment was provided.

The minimal number of adjustments provided in the prototype limited the scope for calibration, but was sufficient for testing and verifying the precision of the instrument. An extension of the instrument design to include full calibration would use non-volatile memory (EEPROM) to store calibration factors. This is preferable to an approach using preset resistors because it is more amenable to automation and more secure. Non-volatile storage would be required in the interface unit and each detector head.

The approach of using non-laser sources which worked well for testing detector performance would be unsuitable for calibration purposes. The non-collimated nature of the LEDs makes it impossible to accurately predict the fraction of source radiation reaching a detector. If the instrument is calibrated optically then laser sources would
be required. An entirely optical calibration routine has the disadvantage of making it complex to determine the separate calibration factors for the interface unit and detector head. These must be extracted from an overall calibration factor so that the interface units and heads can be used interchangeably.

A more appropriate approach is to regard the instrument as having three stages:

1. Interface unit electronic transfer function
2. Detector head electrical transfer function
3. Detector head optical transfer function.

Each of these stages may be calibrated independently. Dividing the calibration task into sections makes it possible to use electrical sources for the majority of the calibrations. Variable voltage and current sources are readily available with sufficient accuracy to act as calibration standards. Using an electrical stimulus directly eliminates the extra uncertainty introduced by electrical to optical conversion. Optical calibration is then only required to compensate for variations in the detector transfer function.

The following sections consider the techniques which could be used to calibrate an instrument. Remaining sources of systematic error are also discussed.

6.5.2 Electronic Calibration techniques

In the prototype, values for critical components such as the gain setting resistors in the head and the integrator capacitors were coded into the software running on the Psion. A complete calibration would require that the values of these components be determined and stored in non-volatile memory. After a measurement these would be transferred to the Psion to be used in the calculation of average irradiance and pulse radiant exposure. It is essential that the calibration factors are stored on the same board as the components concerned so that individual modules (head, interface and computer) can be used interchangeably.

Calibration of the interface unit requires at least four known input voltages. The voltages would be obtained from standards of known accuracy and with calibration
traceable to national standards, preferable through a NAMAS approved laboratory. Each input voltage has to be calculated to give sufficient integrator charge to cause a specific range to be selected. The integrator output voltage as measured by the ADC can then be used to calculate the effective capacitance on each range. This calculation of capacitance includes the effect of the exact voltage gain preceding the integrator. The same input voltages could be used to calibrate the voltage gain of the peak detector. Using more than four standard voltages would permit the linearity of the instrument to be verified on each range.

No specific calibration of the pulse width measurement functions or the timing of the one second measurement period is required because of the high accuracy and stability of the quartz crystal used for the microprocessor clock. Typically the crystal is accurate 50 parts per million which introduces negligible uncertainty. The interrupt handling routines for the microcontroller were written to complete rapidly. This ensured that the counter used to control the one second measurement period was not affected by the counting of pulses or measurement of total exposure duration. The measurement period therefore remains constant regardless of the number or width of any pulses measured in the laser radiation.

Calibration of the detector heads requires a current input for the pyroelectric and photodiode heads and a voltage input for the thermopile. At least one voltage or current is required for each gain value in the detector head, further inputs would permit the linearity to be verified. The exact gain on each range is then determined by measuring the detector head output voltage for each known input. Calibration factors corresponding to the effective gain on each range would then be stored in memory. For the pyroelectric detector head the applied current could be constant rather than pulsed. The negative peak detector output would remain at zero and the head gain would be determined directly from the ratio of output voltage to input current. The detector head output voltage could be measured using a previously calibrated interface unit. This would be convenient, but would limit the accuracy to which the detector head calibration factors could be calculated because of the precision errors associated with the interface unit. A more accurate approach would use a calibrated voltmeter
with accuracy comparable to the voltage or current source for measuring the head output.

It would be possible to build a test source into each detector head so that correct electrical functioning of the instrument could be verified. Low cost semiconductor voltage sources with 1% uncalibrated accuracy are available. These may also be configured as current sources with the addition of a resistor.

6.5.3 Optical Calibration techniques

The final part of the calibration process determines the optical to electrical transfer function of the detector and optical elements. If this is performed subsequent to calibration of the electronic sections then the calibration factors could be based on the ratio of optical input to detector head output. Alternatively the detector output could be used to directly determine the transfer function. The latter approach would provide the greatest accuracy because it would exclude the errors associated with the electronic calibration of the detector head gain.

A radiation source with known and stable output power is required for detector calibration. As an alternative it is possible to use a stable source and determine the power incident on the detector being calibrated using a beam splitter and calibrated power meter. Calibration of the pyroelectric detector requires a chopped or pulsed laser source. An optical pulse train is also required for the thermopile head. Before determining the electrical gain it is necessary to adjust the corner frequency of the frequency boost circuit to match the thermal corner frequency of the thermopile. This adjustment affects the low frequency gain of the filter circuit. If it was found that the thermal corner frequency of the thermopiles was consistent between devices then this adjustment could be eliminated.

Each detector requires optical calibration with all possible combinations of external optics which could be used. In measurement conditions where the laser radiation overfills the detector aperture the accuracy of the aperture diameter is important. Calibrating the aperture area optically would be difficult. A light source with known uniformity of irradiance which overfilled the aperture would be required. It is more
practical to fabricate an aperture with accurately known diameter to avoid the need for
calibration. Techniques are readily available to fabricate apertures with an accuracy of
area of 0.05% [108], more than sufficient for this application. The calibration factors
giving the optical to electronic transfer functions for the detectors and optics would be
stored in the non-volatile memory of the detector head.

Calibration is required at a range of wavelengths for each detector. Thermopile
detectors use a relatively thick black coating to absorb incident radiation, pyroelectric
detectors use a thin metallic coating to supplement absorption by the crystal. Despite
the nominally flat spectral response, calibration at several wavelengths is still necessary
because variations in coating thickness between detectors may affect the spectral
response. In addition, optical components such as attenuators or diffusers which may
be used require calibration across the intended spectral region. For the thermopile and
pyroelectric detectors the most pragmatic approach is to perform calibration at the
most frequently used wavelengths. This implies a calibration at 10.6μm and in the
region 1.5μm to 2μm. Responsivity between these spectral regions may be
interpolated from the calibrated points using the spectral response curves available for
the detectors or coatings. If operation is anticipated at an intermediate wavelength
then a further spot calibration could be performed.

The responsivity of a photodiode is inherently sensitive to wavelength. Short
wavelength responsivity is affected by the collection efficiency of photogenerated
carriers close to the absorbing surface of the diode. Long wave responsivity is affected
by variations in depletion layer depth and charge collection efficiency from beyond the
depletion layer. Variations in long and short wave responsivity are therefore
independent. In the central spectral region the responsivity of certain photodiodes may
be predicted directly from theory [43]. This is termed self-calibration, such devices
may be used directly as reference standards. It was not practical to use these devices
in the instrument because of the need to apply bias to the oxide. The general theory
developed for self calibration is of use because it indicates that a three wavelength
calibration will permit correction for the causes of device to device variation. The
reasoning applies to silicon photodiodes but may be extended to other types because
all photodiodes have a spectral response governed by the same physical factors.
For silicon devices the three calibration wavelengths should lie in the blue, red and infra-red spectral regions. Calibration with blue light (for example an argon-ion laser at 488nm) quantifies the charge collection efficiency close to the device surface. The calibration using infra-red light (for example a gallium-arsenide diode laser at 950nm) quantifies the effect of variations in depletion layer depth and charge collection efficiency beyond the depletion layer. The calibration using red light (for example a helium-neon laser at 633nm) complements the previous calibrations by quantifying overall device efficiency in the spectral region of optimum operation. All calibrations must be performed with the photodiode operating under the same bias conditions as in the detector head.

From the manufacturer's data on the photodiodes [47,55,92] it is apparent that the typical spectral response is monotonic over the spectral ranges used by the instrument. A three point calibration combined with a second or third order polynomial fit enables the responsivity at intermediate wavelengths to be predicted and provides better accuracy than a linear interpolation. It is possible to store either the responsivity at each of the three wavelengths or the coefficients of the polynomial fit in non-volatile memory. In either case, these would be transferred to the Psion after a measurement and used in place of the fixed expression for responsivity used by the prototype. If it was found that three points did not provide sufficient accuracy then it would be straightforward to add further wavelengths to the calibration.

6.5.4 Residual systematic error sources

It is inevitable that calibration will not result in complete removal of systematic errors because the standards used to calibrate against have a finite uncertainty. In this discussion it will be assumed that sources of sufficient accuracy have been used to perform the calibration and that all calibrated residual systematic errors are negligible. The remaining potential sources of error which are not addressed by the calibration procedure described in the previous sections are:

- Change of the detector spectral response profile from the assumed profile.
- Differences between the assumed model of temperature sensitivity and the actual instrument temperature sensitivity.
• Drift in the values of components used to determine the gain.

The use of a three point calibration to determine the spectral response of the photodiode will introduce systematic errors if the detector spectral responsivity deviates from the assumed near linear function of wavelength. Photodiodes are intrinsically sensitive to wavelength and therefore variations of relative spectral response are probable. Budde [46] shows data from a sample of fifteen identical models of silicon photodiodes in which the relative responsivity varied by a maximum of ±7%. It was observed that a well controlled manufacturing process can reduce relative responsivity variations to better than ±0.2%. This is borne out by the work on self calibration of photodiodes which relies on repeatable and predictable relative spectral responsivity [43].

For the thermopile and pyroelectric detectors the responsivity is largely independent of wavelength. It is therefore less probable that variations in relative spectral responsivity will be significant. Variations between detectors of these types are more likely to be in magnitude of responsivity alone.

The correction for temperature was based on detector manufacturer's data for the relationship between temperature and responsivity. This assumes that the detector is the dominant source of temperature sensitivity. If other aspects of the instrument are more temperature sensitive then systematic errors would be introduced when the ambient temperature changed from the value used during calibration. The true temperature dependency of the instrument with each type of detector head could be determined over the operating temperature range. It would then be possible to determine whether the present temperature compensation algorithm was sufficiently accurate or whether a more complex model was appropriate. The temperature compensation function is calculated in software, consequently it would be straightforward to adopt an alternative function.

The photodiode is most susceptible to changes in responsivity with temperature. The thermopile and pyroelectric detectors have a linear, wavelength independent change of responsivity with temperature. Photodiodes have a responsivity which is more temperature dependent at long and short wavelengths, as discussed in Section 2.4.2.1.
These changes could distort the spectral response curve as the temperature changed, requiring the use of a more complex algorithm for correcting the changes in responsivity with temperature.

The effects of component value drift with time were minimised through the use of high stability components. An extended test of the instrument against suitable standards would indicate whether there was a problem with stability. If the temporal stability was found to be insufficient then more stable (but more expensive) components could be used. Alternatively if the effects of component ageing were predictable then a software correction using "time since calibration" could be used to reduce the effect.
6.6 SUMMARY

The prototype instrument performance was investigated by testing the detector heads and interface unit individually. Tests of the detector head performance used both electrical and optical input signals. The silicon photodiode detector head was combined with the interface unit and the computer to permit the performance of the entire instrument to be evaluated.

The noise performance of the silicon photodiode head was compared to a basic transimpedance design with similar bandwidth and two alternative operational amplifier devices. It was found that the output noise of the pulse stretching design was only three times greater than the standard transimpedance circuit, yet the pulse stretching circuit was capable of measuring the energy of short pulses. A bipolar operational amplifier was found to generate less noise than a FET input device. This implied that low voltage noise was the most important operational amplifier parameter.

Electrical inputs were used to verify the response of the detector head to long and short pulses. Pulse widths and repetition rates were selected to demonstrate the response to single short and long pulses, and to high repetition rate short pulse trains. Similar optical inputs were then used and found to give similar output signals. A frequency doubled Nd:YAG laser was used to demonstrate the operation of the pulse stretching detector head for a short pulse of high peak power.

The pyroelectric detector head operation was verified using electrical input signals to demonstrate the response to pulse trains at the maximum and minimum designed repetition rates and widths. It was found that the d.c. restoration function operated as required and that the detector head output was in a suitable unipolar format. Optical inputs were used to spot check the electrical input results and to verify the linearity of the detector head.

The response of the thermopile detector head to optical pulses with and without the frequency boost circuit was investigated. It was found that the detector head output using the frequency boost had a rise time of 5ms, sufficient for the design aim of
resolving 50ms pulses. The increase in noise introduced by the frequency boost did not cause problems.

Electrical inputs were used to test the operation of the interface unit. The response speed and accuracy of the peak detector were verified and the linearity of the auto-ranging integrator demonstrated.

A series of tests of the entire instrument with silicon photodiode detector head was performed to determine the instrument precision. The most stable optical source was a purpose designed array of LEDs. A rotary laser scanner was used and found to give comparable precision results. The instrument performance exceeded the requirements of Class 10. A display laser system was used to determine the measurement precision under representative operational conditions. It was found that the measurement precision was reduced, primarily because of non-repeatability in the laser scanning equipment. This confirmed that in a typical application the source rather than the instrument would dictate the measurement precision.

Overall measurement accuracy is a function of the precision errors and the systematic errors. Systematic errors are reduced by calibration. A full instrument calibration was not performed, determination of the instrument precision alone was a more useful indicator of the instrument performance. The techniques for instrument calibration to reduce systematic errors and therefore ensure measurement accuracy were discussed.

Electrical calibration signals were proposed for the interface unit and for the detector head electronics. Optical inputs were then only required for calibration of the detector transfer function. Performing the majority of calibration electrically has the advantage that suitable sources are readily available and it becomes straightforward to separate the calibration factors of the detector heads and the interface unit so that the modules may be used interchangeably. Calibration factors for a final instrument would be stored in non-volatile memory rather than variable resistors as in the prototype.

After an instrument has been calibrated, some systematic errors remain. The sources of these residual systematic errors and also the sources of precision errors were discussed.
EXTENSION OF THE INSTRUMENT FUNCTIONALITY

7.1 INTRODUCTION

The prototype instrument was developed to address problems in making assessments of laser radiation for hazard assessment purposes. A modular solution was designed to minimise the cost overhead inherent in the need to use several detector types to address the full spectral range. The task of radiation hazard assessment was identified as being critical in laser safety and accordingly the solution was fully developed. It was intended that the modular approach would permit the instrument to be modified for other measurement functions related to the task of laser safety and to laser operation more generally.

The use of the instrument in new applications would conform to the existing modular structure. The Psion computer would perform data processing, interpretation of any necessary standards and information display. The interface unit would extract the essential data from the detector head outputs. New detector heads would convert the measurand to the standard electrical signal format used by the interface unit. The design approach of using a generic interface unit with data processing being performed in the computer ensures that it is only necessary to write new software to process the data provided by new detector heads. The ability to apply the instrument to new measurement tasks demonstrates the advantage of the modular concept.

An alternative application was highlighted during preliminary trials of the instrument. Users appreciated the ability to perform the radiation hazard analysis but wanted to use the instrument for more general laser power and energy measurement. The prototype instrument has measurement specifications and functions exceeding those of many commercially available meters and would therefore be ideally suited to a more general measurement role. It would be possible to consider the use of the instrument primarily for laser power and energy measurement, but with dedicated functions for laser hazard assessment. This could be achieved by modification to the Psion software alone; the existing hardware would remain unchanged. The increased functionality obtained by including general laser power and energy measurement would make the instrument...
economically viable for more users. The major problem for a more general laser power and energy meter is the potential need for high average power measurements.

The detectors used for the prototype instrument were suitable for measuring average optical powers of several milliwatts. It is possible to extend the upper power limit to between 1W and 10W using optical attenuators. Operation at higher powers is limited by the power dissipation permissible in the attenuator.

Thermal detectors suitable for measurement of high laser powers are available commercially for operation to 5kW [Coherent Inc. LM-5000]. Water cooling is required, it is necessary to control water temperature and flow rates if the measurement accuracy is not to be degraded. This is inconvenient for field use. The large physical mass of high power detectors causes a slow response (10s - 15s is typical) and limits operation to a measurement of average power.

An alternative approach to the problem of measuring high average powers is to take a small sample of the laser beam and use this for measurement. Using a small sampling ratio makes the measurement non-invasive and avoids the need for a detector capable of dissipating significant power. It then becomes possible to use the detector technology applied to MPE assessments. Measurements are no longer limited to average power, it is also possible to resolve pulses. If the sampling technique provides an accurately known fraction of the incident beam then the measurement accuracy will be determined by that of the low power detector and instrument; Class 10 or better. A laser beam sampling approach to high power measurement is described in this chapter.

An important aspect of laser safety is ensuring the integrity of high power laser beam delivery systems. A method of beam delivery monitoring evolved from the high power laser measurement technique. The application of non-invasive laser power measurement for process control is also discussed.

A sensor strategy for the analysis of gaseous fume generated by laser processing of polymers was also investigated. This was a novel application of "electronic nose" technology using metal oxide gas sensors. It was found that the nose was capable of differentiating the fume generated from processing of different polymers. The nose
was not integrated into the modular instrument during the preliminary investigations. As part of the modular instrument (or as an independent system) this work would be of use in warning of possible fume hazards, verifying correct fume filtration performance, predicting filter ageing and potentially in process control. Further details of the work have been published previously [109].

7.2 HIGH POWER LASER BEAM MEASUREMENT

7.2.1 Laser beam sampling techniques

Beam samplers may be transmissive or reflective. Generally reflective beam samplers are preferable because a reflective sampler may be cooled more easily than a transmissive sampler. Consequently reflective beam samplers can be expected to be more reliable with high power laser beams. Hole matrix mirrors and diffractive mirrors are examples of reflective beam samplers. The operation of the hole matrix mirror has been described by O'Key et al. [110]; a sample of the main beam is taken through the mirror using an array of small holes. The sample ratio is determined physically by the ratio of hole diameter to hole spacing. A disadvantage is that a lens is required to reconstruct the sample beam. A diffractive mirror uses a standard mirror (oxygen free high conductivity copper for CO₂ lasers) with a diffraction grating diamond turned on the surface. The diffraction grating is designed to reflect a known fraction of the main beam at a specific angle at a given wavelength with a very low insertion loss. Typically a sampling ratio of 0.05% would be used, careful design ensures that the sample ratio is accurately known. An alternative sampling method uses the leakage through a standard high reflectivity dielectric mirror. This provides a sampling ratio of approximately 0.1% [110], but has the disadvantage of being non-repeatable between mirrors, sensitive to angle of incidence and temperature. Hole Matrix Mirrors and Diffractive Mirrors give a sample ratio determined by their physical construction. The diffractive mirror is to be preferred since it does not require an additional lens for operation, consequently the unit can be made compact and can directly replace an existing turning mirror in the beam delivery system.
7.2.2 Laser power measurement applications using the beam sampling mirror

It was found during the investigation of the radiation hazards associated with high power CO₂ laser material processing (Section 3.2.1) that the ability to measure the incident laser power would be a benefit. Assessments of the radiation scattered and reflected from the workpiece could then be related to the incident power. This would make comparisons between individual assessments and between different processing conditions valid. Other parameters, such as laser tube current could be used as indicators of power, but these are not reliable methods for determining the actual power incident on the workpiece.

A detector head for high power laser measurement could be constructed for the Psion based meter using a standard detector head design and the beam sampling mirror. This would enable on-line power measurement. Such a head would be suitable for single laser wavelength operation only. This is not a significant disadvantage; the majority of measurement applications could be addressed by designing heads for CO₂ and Nd:YAG lasers.

An additional application of the proposed laser power measurement technique would be in process control. The measurement and control of laser power is an important aspect of a process control system [111]. For process control the laser power measurement must be performed continuously. The non-invasive nature of the beam sampling mirror makes this possible. The low power incident on the detectors permits the use of physically small devices with rapid response times. Short term instability in the beam power is readily detected. The output of the detectors would be used by a dedicated process control system, possibly based around a PC rather than the Psion based instrument.

For the measurement of c.w. laser power, or the average power of pulsed lasers the low power thermopile detector head design would be used. Measurements on pulsed lasers could be performed by substituting the pyroelectric detector head for the thermopile detector head.
7.2.3 Laser beam delivery monitoring applications using the beam sampling mirror

The use of a beam sampling mirror to provide a real-time measure of laser power can provide additional safety features for a laser material processing system. Industrial applications usually require that the laser installation is a Class 1 laser product as defined by BS EN 60825 [3]. The standard specifies that the classification be performed under both normal operating conditions and reasonably foreseeable single fault conditions. Fault conditions imply that the laser radiation is not reaching the desired target. The hazard arising from this errant beam must be controlled. It is important that hazard control measures are effective, but they must not be any more restrictive than necessary. Current approaches may be divided into passive or active control measures. A passive approach, also termed the fortress approach, relies on an enclosure to resist the thermal or optical effects of the laser radiation and to contain the laser beam during fault conditions. An active approach detects the fault condition and responds to remove the hazard by switching off the laser.

A passive approach will usually be in conflict with the desire for flexible operation and rapid flow of workpieces through the system. Active approaches can permit more flexible operation with minimal guarding for normal operation, whilst still maintaining acceptable safety levels [112]. To distinguish between the two approaches to active hazard control two terms are used in this work. The first approach, in which the system responds to the effect of an errant laser beam, is termed reactive. A reactive system requires an errant laser beam to exist and for it to start burning the enclosure. Enclosure damage may be detected via the heating effect of the laser beam, or by allowing the laser to burn through a sacrificial layer and detecting the resultant damage. The second active approach is termed proactive. A proactive system detects a developing fault and removes the hazard of an errant beam without the need for the enclosure to be damaged.

The beam delivery system presents the greatest number of potential fault conditions and accordingly the highest probability of an Errant Laser Beam Occurrence (ELBO) [113]. Failure modes include misalignment of the flight tubes or optics arising from gradual displacement by vibration or sudden displacement caused by impact, omission
of components after incorrect servicing or contamination of the optics. Even when the radiation has been correctly delivered a workpiece fault such as incorrect alignment could cause an ELBO.

Edwards and Bandle [113] show that the total probability of a fault occurring in the delivery system is at least an order of magnitude higher than for one related to the workpiece. A typical workpiece fault condition would be incorrect alignment of the workpiece causing a specular reflection of the incident laser beam. In this case the reflected radiation is likely to be divergent, reducing the distance at which a radiation hazard exists.

Given the significantly higher probability of a fault developing in the delivery system it is appropriate to concentrate the application of hazard control measures to this area. A fault condition in the beam delivery system will result in overheating of the flight tubes or optical components and a loss of power at the point of interaction. Fault conditions can therefore be detected by measuring the laser power as close to the point of interaction as possible. Usually this would be the final turning mirror in the beam delivery system. Replacing the final mirror in the delivery system with a beam sampling mirror is an ideal method of monitoring delivered power. This power is compared to the output power of the laser, either in real time or by comparison to an initial calibration under correct operation. If the two values are in agreement then the system is operating correctly, otherwise a fault exists. By placing upper and lower bounds on the acceptable power an errant laser beam need not occur, a gradual decrease in delivery efficiency can be signalled before the process is affected or any hazard exists. Such a system provides proactive fault detection. Monitoring for beam over and under power reduces the probability of a failure in the fault detection system preventing a genuine fault from being detected. A fault such as an open circuit detector would give an output indicating a high measured power. If the measured power only had to exceed a threshold for the laser to be classed as operating correctly then such a fault in the monitoring equipment could conceal an errant laser beam condition.
A development of the power measurement application is to use a position sensitive detector to indicate movements in the sampled beam and by implication changes in the angle of incidence or position of the main beam. Such a system monitors the stability of both beam power and position. Deviations from the ideal alignment can provide substantial prior warning of misalignment before either the process is affected, or any hazard exists. As such it implements proactive hazard control based on two laser beam parameters. By monitoring two parameters the probability of a fault in the monitoring system obscuring a genuine ELBO can be further reduced. All detector elements must be giving a satisfactory signal before the laser can operate.

An additional advantage of such position sensing is that the process of aligning the delivery system can be simplified. If the diffractive mirror is mounted at precisely 45° to the input and output ports then it can be used as a reference for aligning the other optical components. Initial alignment of the system would still use a visible laser, coaxial with the main beam. The outputs of the position sensitive detector then provide guidance for the final adjustment. It would be possible to use the Psion based instrument as a display module for the alignment process. Audible and visual indication of the beam position could be provided. Since beam alignment is an important aspect of laser safety [114] a simplification of the process is valuable.

The bi-directional nature of the diffractive mirror made it possible to use the sample in the forward direction (main beam) for position and power sensing and the sample in the reverse direction to measure the amount of back reflected radiation. By measuring the back-reflected power some aspects of the delivery system beyond the diffractive mirror could be supervised. For example a misaligned nozzle would generate back-reflection as the beam was clipped, a missing lens would give significant back-reflection from around the nozzle and a damaged lens would generate increased back-reflection from the optical imperfections.

7.2.4 Trial implementation of the beam sampling mirror

The use of a beam sampling mirror for on-line power measurement was combined with a simple beam delivery monitor in the first implementation. The diffractive mirror was used to replace the final mirror of the delivery system. A thin film thermopile (Dexter
2MC) was installed in the forward sampling port to intercept the first order of the diffraction pattern. This has a sensitive area considerably smaller than the sampled beam. As a consequence the detector output was not a function of total beam power alone, the beam power, position and mode interacted. For a measurement of total laser power this would be a disadvantage. It was regarded as an advantage in the beam delivery monitoring system because a change in beam power, position or mode could signify a developing fault in the laser or delivery system with safety or process quality implications. The system therefore acts as a "deviation from ideal" detector. If an absolute measure of beam power is required then a larger detector or collecting lens could be used.

A preamplifier was situated adjacent to the thermopile to minimise noise pickup and provide a buffered voltage proportional to power incident on the detector. The gain of the preamplifier was adjustable to permit calibration of the indicated power for a given laser beam diameter and mode structure. A low pass filter was used to prevent unwanted noise from being amplified, the cut off frequency matched that of the thermopile. Together these limited the electronic response time to approximately 100ms. There was no advantage to be gained by faster operation because the mechanical shutter response time limited the overall response time. If the circuit was used to directly control the power supply to the laser then an increased electronic response speed would be useful. Some improvements in response time with a thermopile detector could be obtained using the frequency compensation technique applied in the design of the thermopile detector head (Section 4.4.4). Ultimately noise would limit the application of this technique, and a faster, but more expensive detector such as HgCdTe would be required. Alternatively if the laser operated in a pulsed mode then a pyroelectric detector could be used. A design similar to that described in Section 4.3.4 would be of use.

A separate unit was used to process the output of the preamplifier. Laser power was displayed, the accuracy of this display as a measure of true laser power was subject to the sensitivities to mode and position described earlier. Two comparators were used to detect the beam under and over power conditions. The threshold voltages were set by potentiometers supplied from a voltage reference.
A relay was driven from the comparator outputs, if either comparator output changed state then the relay latched open. The relay was the last in the chain of interlocks and controls which govern shutter operation. The shutter was internal to the laser enclosure and when closed prevented any radiation entering the delivery system. Shutter closure was ensured by a gravity assisted spring. A signal was taken from the interlock circuit to the relay control circuit which over-rove the comparator outputs for approximately 0.5s to allow the measured power to exceed the lower threshold. The duration of this over-ride was minimised because it also causes genuine fault conditions to be over-ridden briefly on every attempted start of processing.

To investigate the feasibility of beam position monitoring using the beam sampling mirror the single element thermopile was removed from the sampling port and replaced with a dual element device (Dexter DR34). Ideally a quadrant thermopile would have been used but no device with sufficient sensitivity was available. Having only two elements results in a position sensing ability which is maximum for displacements perpendicular to the elements and zero for displacements parallel to the elements. For alignment purposes this is not a significant problem as the detector may be rotated through 90°, ideal alignment being the case where the output of the two elements remains equal throughout the rotation.

The sensitive area of the DR46 was substantially less than that of the sampled beam. The sensitive areas were separated by approximately 1mm. Positional sensitivity could be increased by focusing the sample beam onto the detector, but if the detector was placed in the focal plane then a misleading central null in the outputs would occur. To minimise cost and complexity a lens was not used. Limited positional sensitivity would only be a problem with large diameter beams having slowly changing intensity profiles.

A preamplifier and low pass filter similar to that used with the single element device was used to amplify each detector element output. These outputs were sampled at 10Hz by a data acquisition system. Beam power was calculated as the sum of element outputs, the position by the difference of the element outputs divided by the sum. In a practical system these calculations could be implemented electronically using analogue adders, subtractors and dividers.
7.2.5 Results of the trial implementation

The beam power monitor utilising a single thermopile detector was installed on a 500W Coherent 525 Everlase CO₂ laser system. The gain of the preamplifier was adjusted to give an output of 1mV/W, calibration being performed using a Coherent LM-1000 head as the reference. A digital voltmeter module was used to provide a direct indication of laser power in watts and to simplify the setting of maximum and minimum power thresholds. The accurate display of laser power provided by the system has meant that it is regarded as a beneficial addition to the laser rather than a restrictive safety measure.

The position sensing beam monitor was tested using the arrangement shown in Figure 7.1. A linear stage was used to displace the blank copper mirror along the axis of the incoming laser beam. This caused an equal linear displacement on the diffractive mirror. Figure 7.2 shows the individual outputs of the thermopile elements (normalised to a peak value of unity) and the calculated beam position. The thermopile elements were aligned for maximum sensitivity to the direction of displacement. Positional information was only recorded over the central region where both detectors were providing significant outputs. The increase in detector B output at the end of the scan was attributed to the edge of the main beam reaching the detector. The linear displacement of approximately 1mm between the thermopile outputs corresponds to the linear separation of the thermopile elements. The change in detected beam position was approximately linear with the displacement of the mirror over the central region of the displacement ($r = 0.994$).

The position sensing system was then tested on the Coherent Everlase system. The twin element thermopile was temporarily used to replace the power monitoring thermopile in the forward sampling port. A single element thermopile was fitted to the reverse sampling port to measure the backreflected laser radiation. A laser power of approximately 200W was used to cut Medium Density Fibreboard (MDF). A nozzle diameter of 0.8mm was used. Beam positional errors were artificially introduced by adjusting the positioning screws on the mirror preceding the beam sampling mirror. A rotation of half a turn in each direction of the screw was used, it was not possible to
relate these changes to a simple positional or angular change in beam position. An approximate step change in beam position was generated by turning the screw rapidly. The sequence of positional error generation was to start in the equilibrium (correctly aligned) position for approximately 20s, rotate half a turn anticlockwise for approximately 20s, return to the equilibrium position for 20s, rotate half a turn clockwise for 20s and finally return to the equilibrium position. The results are shown in Figure 7.3.

The increase in back-reflection at the start and end of the results corresponded to the opening and closing of the shutter. Contributions to the measured back reflection originated from reflection from the lens, from the nozzle, from the workpiece and the diffuse component of the diffractive mirror. The position sensing information was only valid whilst the shutter was open, at other times it was suppressed. It can be seen that the recorded beam position corresponded to the changes in beam position caused by the rotation of the mirror adjustment screws. Minor variations in indicated position resulted from the cumulative affects of beam pointing instability, lack of rigidity in the mirror position whilst the adjustment screws were being used and electronic noise in the preamplifiers and thermopile elements. Back-reflection increased once the beam
position deviated from a central position. This was caused by the edge of the focused laser beam clipping the nozzle. A reference measurement was taken with the alignment unchanged. It was found that the peak to peak noise in back-reflection was approximately 4% of the value when the beam was misaligned. The peak to peak noise in position was approximately 20% of the misaligned value. Noise was more significant in position measurement because the normalisation process used the difference in two small values. Long term (60s or longer) averaging would greatly reduce the noise in the position measurement.

7.2.6 Integration of the beam sampling mirror into the modular instrument

Sensor techniques for the new applications were developed independently of the Psion system. Where data acquisition was required this was implemented using a standard PC based data acquisition system. The overhead in developing sensor specific software on the Psion was thereby avoided. Once the sensor had been characterised it was possible to determine the optimum means of interfacing to the Psion based system utilising the modular architecture.

Measurement of beam power or energy with the prototype system could use the same circuits as the thermopile and pyroelectric detector head prototypes. Low beam power or large beam diameter might require the use of a lens with the pyroelectric detector to
ensure sufficient optical input. If the detectors were not used for on-line power or energy measurement a beam dump would be required to absorb the majority of the incident laser radiation. This could be air cooled, or in extreme cases for continuous operation at high powers water cooling would be required. The cooling requirements for the beam dump would be less stringent than for the high power thermal detector heads because it would only be necessary to avoid thermal damage to the beam dump, rather than to maintain a stable reference temperature for the detector. Thermal isolation between the thermopile and beam dump would be necessary. When using the thermopile detector it would be important that the beam dump was not within the field of view of the detector because infrared emission from the dump would introduce errors. The insensitivity of the pyroelectric detector to c.w. radiation would exclude such errors.

The use of the beam sampling mirror in a beam delivery monitoring system would not require integration into the modular instrument. In these applications the permanent inclusion of the Psion would be an unnecessary overhead. An interface to the Psion based instrument would be beneficial where the measurements required are intermittent rather than continuous. Typically this could be where the beam sampling mirror has been installed permanently on a laser processing system and is normally used in standalone mode, but where measurements are required as part of a periodic safety assessment. Extending the safety audit to include a check of the beam position and back reflected levels would increase the value of the assessment.

In the case of the position sensing detector, two or four analogue inputs would be required. The single analogue input of the interface unit could therefore be multiplexed to each amplified detector output in turn under control of the digital outputs of the interface unit. If faster processing of the analogue inputs was required (for example when used as a beam alignment aid) it would be simple to modify the interface unit ADC multiplex input to accept additional external inputs. These could bypass the peak detector and integrator.

Where the laser material processing installation is part of a quality controlled manufacturing system it would be appropriate to perform regular checks that the laser
was operating correctly. A reliable and objective approach would be to connect the Psion based instrument to the beam power and position detector outputs to gather the data. Software on the Psion would then record the details of the installation, performance data and date. Repeating this regularly throughout the manufacturing environment on all equipment would build a detailed record of machine operational stability.
7.3 SUMMARY

A diffractive mirror was used to sample a small fraction of a CO₂ laser beam by replacing the final mirror in the beam delivery system. This extended the concept of the modular instrument design to permit the measurement of high power laser beams using the low cost, low power, high speed detectors used for MPE assessments. It became apparent that the technique had broader applications within laser safety. A means of measuring the power close to the processing point permitted the integrity of the delivery system to be continuously monitored. A further development was the use of a twin element detector to combine beam position monitoring with beam power measurement. A second detector was used to measure the sample of the radiation reflected back from beyond the mirror. A thorough monitor of the delivery system was then possible; changes in incident beam power or position could be detected, as could misaligned or damaged components at the cutting head. This permitted proactive detection of fault conditions.

The underlying concepts of the modular instrument were important in facilitating the extension in functionality. Using software for the majority of task specific operations made the instrument adaptable. Modular hardware minimised the duplication in designing detector heads for specific tasks. Had a hardware specific design been used, these new inputs could not have been supported. Individual functions, such as high power beam measurement could have been achieved, but only by constructing another task specific instrument and duplicating much of the data conversion and user interface. Instead an instrument has been constructed which can be applied to measurement tasks distinct from the original requirements.

A further application for the on-line power measurement technique was envisaged to be in process control. The input power or pulse energy is an important parameter. Continuous monitoring of the input to the process makes it possible to control the input and prevent natural variations from affecting the process quality. Process control is important in making laser processing more cost effective.
The hazard associated with the laser radiation is one of the major aspects of laser safety. International standards exist which provide guidance on laser safety and define maximum permissible exposures below which injury should not occur. It is necessary to compare the MPE to the accessible level of radiation to determine whether a hazard exists. This conceptually simple process involves practical difficulties. Initial estimates of laser radiation hazard may be made by modelling the laser system and calculating the levels of radiation to which a person could be exposed. Measurement of laser radiation as part of a hazard assessment is appropriate to confirm the validity of the laser system model and calculations. In some applications it is possible to completely enclose the laser system to prevent any exposure to laser radiation. Where this is impractical, and the system is too complex to model exactly, measurements are essential as a means of determining the potential hazard presented by the system.

It is shown by analysis of the MPE expressions provided in the standard that the measurement requirements are complex. Measurement of energy is fundamental to determining radiation hazard. Examination, both theoretically and practically, of typical commercially available laser power and energy measurement equipment revealed limitations for radiation hazard assessment purposes. Similarly no purpose designed instrumentation was found to fully address the needs of laser radiation hazard assessment. Consideration of the requirements of the various user groups showed that neither the information provided by the standards, nor the available instrumentation was appropriate to the requirements.

Investigation of the physical constraints on laser radiation measurement showed that suitable detectors were available. Three different types were required to permit measurements to be made on the majority of common lasers. A modular design strategy was used to accommodate the range of detectors. Three modular functions were adopted; detector heads, an interface unit and software running on a palmtop computer.

Each detector head was designed to compensate for any detector specific performance limitations and to provide a standard range of output voltages. The importance of
energy measurement revealed by analysis of the standards led to the design of a photodiode detector head capable of measuring the energy of short pulses without requiring high speed electronic hardware. A single interface unit was used to extract the appropriate parameters from the detector head output. This data was then used by the software running on the computer to determine the measured radiation, calculate the appropriate MPE and indicate to the user the radiation hazard. The software also provided guidance to the user at each stage of a measurement and was able to detect and warn of possible error conditions. The majority of the task specific data processing was performed by software. This ensured that modifications to the instrument operation were relatively easy to make.

The design of the instrument raised many issues; selection of appropriate detectors, preventing detector damage, determining which parameters of the laser radiation to measure, selection of appropriate circuit configurations and defining the needs of the various types of user. Examination of the available literature, detailed analysis of the standards defining permissible exposure levels and experimental investigation were required to address the design issues.

The testing of the prototype instrument involved applying a range of optical and electronic signals to the detector heads, interface unit and complete instrument. Initial testing used the inputs to verify that the signal processing operated as expected. Subsequent tests of the entire instrument were performed to estimate the magnitude of precision errors. Calibration techniques for reducing the systematic errors were described. The tests for estimating the precision errors used known stable optical sources. Instrument trials were also performed using a display laser system, a typical application. It was found that the precision of the instrument was greater than the stability of the display source.

The user response to the instrument was extremely positive. It was generally found that the instrument was easy to use and that human errors were successfully prevented. It was suggested that the instrument would benefit from the ability to make more general laser power and energy measurements with hazard calculations being an additional option. The prototype had better measurement specifications than many
commercially available instruments. Such modifications could be accommodated by a change to the computer software alone. Following the completion of the research project the prototype instrument has been developed commercially. The commercial instrument uses the hardware and software designed during the research project and has a case designed to facilitate field use.

A beam sampling technique for the measurement of high power laser beams using the same low power detectors as for MPE assessments was investigated. This work provided a solution to the need to measure the power of high power lasers within the modular concept.

The high power beam sampling technique was found to have applications beyond being integrated to the modular instrument. A strategy for monitoring the integrity of a high power laser beam delivery system was based around the beam sampling technique. The non-invasive measurement of laser power was expected to be of use in the process control of laser material processing.

The work involved in the research project had several novel aspects. These are highlighted below.

- During the analysis of the measurement requirements it was identified that energy measurement was a critical to the assessment process. Total energy over a measurement period was recorded using an integrator in the interface unit. Where pulse trains are being assessed it is important that the presence of deviant pulses having greater than average energy is detected. Analysis of the MPE values indicates that throughout the visible and near infrared spectral regions it is necessary to resolve pulses longer than 18\(\mu\)s. Pulse width is a significant factor in determining the MPE. Detection of the maximum pulse power and comparison to the average power is sufficient to identify deviant pulses. For shorter pulses it is not necessary to measure the pulse width to determine the hazard. Accurate measurement of pulse energy is required, unless the repetition rate is greater than 56kHz, in which case a measurement of the total energy is sufficient. Detection of the maximum pulse energy and comparison to the average pulse energy is necessary to identify deviant pulses.
These measurement requirements were addressed using a novel design of photodiode detector head. This had negligible effect on pulses longer than 18μs, but acted as a pulse stretching, energy conserving stage for shorter pulses. The output pulse width was fixed by the head design, for short pulses the maximum detector head output voltage therefore became proportional to the pulse energy as required. The local, short term integration and pulse stretching provided by the detector head design meant that the instrument was suited to short pulse hazard assessments without requiring wide bandwidth electronics. This was important to minimise the noise which could otherwise have affected the measurement of high peak power, low average power pulse trains and which would have increased the instrument cost. With this design it was possible to measure c.w. laser radiation, or pulses of nanosecond duration with one detector head design whilst still obtaining appropriate data for hazard assessments.

- Detector interfaces were developed for pyroelectric and thermopile detectors to overcome specific limitations. The pyroelectric detector head restored a true d.c. level to the detector output which made it possible to use the signal directly for the measurement of pulse power. A frequency compensation technique was used with a thin film thermopile detector to increase the apparent detector bandwidth. The circuit design used had an advantage over previous designs that the detector was isolated from the filter, consequently variations between detectors did not affect the filter response.

- The practical study of laser displays revealed a significant radiation hazard associated with audience scanning. It had been erroneously assumed previously that it was possible to minimise the hazard by using fast scan rates. This error was compounded by the use of inappropriate instrumentation for hazard assessment. The main concern in the display industry had been to detect failure of the scanning system without appreciating that even normal operation presented a hazard. Work on this and other display laser hazards was subsequently continued by the National Radiological Protection Board.

- The development of an instrument which addressed the entire task of laser radiation hazard assessment; both measurement and calculation aspects. The
standards were analysed in detail to define the actual measurement requirements. This ensured that the solution was optimised to the task and was not unnecessarily complex and costly.

- A method of extending the operation of the instrument for general purpose laser power and energy measurement was demonstrated. A beam sampling technique was used to provide powers suitable for the low power detectors used in MPE assessment. This provides an accurate means of measuring laser power and resolving the detail of pulsed lasers. A system capable of proactive laser beam delivery monitoring was also demonstrated using the beam sampling technique. The system was capable of monitoring the laser beam power and position at the final mirror in the delivery system besides the condition and alignment of optical components at the processing head. Any deviation from ideal could be used to shut down the laser before a radiation hazard existed.
The development of the prototype instrument proved the practicality of producing an instrument for laser radiation hazard assessment. Further work would be required to refine the prototype and produce an instrument suitable for general purpose use. During the instrument development other interesting applications of the measurement technology were discovered and investigated. Constraints of time meant that these could not be fully evaluated. Areas for further work may be divided between those relating directly to the radiation hazard evaluation instrument and those relating to other measurement applications.

9.1 INSTRUMENT DEVELOPMENT

The photodiode detector head design was evaluated using a silicon photodiode. This was suitable for measurement of many common laser types, but alternative photodiode types would be required to extend the measurement range into the infrared (950nm to 1500nm) and ultraviolet (180nm to 400nm). Suitable photodiode types have been proposed and the design used for the silicon photodiode would be applicable to alternative photodiode types. The experimental procedure used to select the optimum silicon photodiode would need to be repeated, again with particular emphasis on short pulse response.

The component values in the pulse stretching circuit would require recalculation to give appropriate gain and output pulse widths for the new photodiodes. Additional software would be required in the Psion computer to support the new detector types. New functions would include the calculation of detector responsivity for the new devices and modifications to the user interface to prompt for any additional information (for example pulse width for ultraviolet measurements) and to provide instructions on the use of the new heads.

If measurements on short (<50μs) pulses were required with the pyroelectric detector head then it would be necessary to redesign the prototype circuit to increase the bandwidth. Care would be required to ensure that the increase in bandwidth did not
bring an increase in noise. As an alternative it would be possible to use the thermopile detector head to measure the average irradiance of a repetitive train of short pulses. The user would be required to enter values of pulse width and repetition rate for certain pulses so that the pulse energy could be estimated.

Not all the user functions were implemented in the prototype Psion software. It would be relatively straightforward to write code to support the functions of saving and retrieving data and printing reports.

The optical design of the detector heads would benefit from refinement. The simple lens based optics were acknowledged to have limitations, but were suitable for testing purposes. It would be necessary to develop a suitable non-imaging reflective optical concentrator as an optimum means of collecting radiation onto the detectors. The design of a concentrator for the thermopile detector would have to reduce the spatial non-uniformity of the responsivity. Attenuators would be required for various spectral regions and pulse widths. Once the optical design was complete it would be advisable to verify that the theoretically determined damage thresholds did compare to practical damage thresholds of the final detector heads.

It would be necessary to add non-volatile memory to the interface unit and each detector head to store calibration data. The microcontroller code and Psion software would need to be modified to make use of the calibration data. Full calibration of each detector head could then be performed. It would then be possible to determine the suitability of the proposed calibration process and make any modifications required. As part of this work the stability of each detector head over temperature and time would require verification.

Once the calibration requirements were known and a full instrument calibration performed it would be possible to determine the instrument accuracy based on precision and residual systematic errors. The borderline condition could then be implemented. As part of this work it would be useful to experimentally determine the magnitude of errors introduced by the user (for example misalignment). This would verify that the design of the detector optics did make alignment straightforward.
9.2 ALTERNATIVE MEASUREMENT APPLICATIONS

The method of laser beam power and position monitoring was expected to be of use in process control. Further work would be required to determine the sensitivity of critical processing parameters to the laser beam power and position so that the accuracy to which a closed loop power and position control system would have to operate could be defined. The beam power feedback would be linked to the laser power supply to provide closed loop control of laser power. The beam position feedback would be used to control a motorised mirror mount at some point before the beam sampling mirror to provide a constant beam position. Use of a quadrant detector to replace the twin element device used in the initial experiments would be necessary if the control of beam position was to be accurate.

Methods of laser wavelength measurement had been considered and the combination of a silicon photodiode and thin film thermopile had been shown to provide a wavelength dependent output signal (Appendix 7). Further development was not justified at the time because of the limited need for laser wavelength measurement during hazard assessments and the need to concentrate design effort on other aspects of the instrument. It would be useful to develop the concept further to determine the potential of the method. Fundamental to the performance is the method of radiation division. A comparison of the proposed methods would be required. Particular problems could be encountered given the spatial non-uniformity of the thermopile detector. Once the system had been proved with a silicon photodiode, the addition of an InGaAs photodiode would permit laser wavelength measurement at near infrared wavelengths.

The modular instrument design would be a suitable basis for the development of further radiation hazard assessment equipment. This would not necessarily be limited to laser radiation safety. Examples are a detector for assessing the hazard of broadband (non-laser) ultraviolet radiation and the "blue light" hazard associated with some material processing applications. Such detectors would require the design and construction of dedicated detector heads and new software to interpret the measurement data, but the instrument strategy would remain unaltered.
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The linear drive board was designed to generate analogue optical signals. Analogue signals were required during detector evaluation and detector head testing to investigate linearity. The linear drive board was capable of driving up to five LEDs to permit greater optical powers to be generated. A output stage provided a constant current supply to each LED proportional to the input voltage. The proportionality of LED output power to the forward current ensured that the output power was approximately proportional to the control voltage.

Figure A1.1 shows the simplified circuit of one of the five drive channels. Current is regulated by feedback from the emitter resistor. The voltage applied to the non-inverting operational amplifier input causes a current to flow through the emitter resistor such that the voltage drop across the emitter resistor is equal to the input voltage. A constant current therefore flows through the LED, controlled by the input voltage. It was possible to select either high brightness visible LEDs (Hewlett Packard HLMP8103 - centre wavelength 637nm) or high power infrared LEDs (Telefunken TSUS5202 - centre wavelength 950nm). The maximum drive current (for a 1V input signal) was 25mA for the visible LEDs and 100mA for the infrared LEDs. At these maximum currents the relationship between current and LED brightness became non-linear. This was because the power dissipated caused the LED temperature to increase, reducing the efficiency of electrical to optical conversion. The plastic package of the LEDs prevented thermal stabilisation of the active element using an external heatsink.

A machined aluminium block was used to align the five LEDs and the detector under test. The block was designed so that one LED was on the detector axis, the remainder were at an angle of approximately $30^\circ$ to the detector axis. LEDs with a narrow emission angle were used to provide maximum coupling with the detector. This was helped by the reflective finish of the aluminium block.
It was found using a photodiode with a response time known to be faster than 100 ns that the linear LED drive board had a rise time of approximately 1 μs.

Figure A1.1: Diagram of one channel of the linear LED drive circuit.
An alternative LED drive board was developed to provide a pulsed optical signal with short rise and fall times. Figure A2.1 shows the simplified design. A pulse generator was used to provide an input signal. The Schmitt input inverters ensured that the rise time of the drive pulse was minimised (below 10ns). It was also possible to invert the sense of the input pulse. This provided optical signals with duty cycles not conveniently available from the pulse generator. A resistor was connected across the LED to ensure rapid removal of charge carriers from the junction at switch off. Without this resistor the LED was left floating when the drive transistor switched off and it was found that this introduced a long tail to the optical pulse. The resistor ensured that charge carriers were rapidly removed from the LED without having time to recombine and generate light.

A single high brightness LED was used with the pulse drive board (Hewlett Packard HLMP8103 - centre wavelength 637nm). The series resistor was selected to give a pulse current of 20mA. An aluminium block was machined to hold the LED and detector coaxially.

![Diagram of the pulsed LED circuit.](image)

Figure A2.1: Diagram of the pulsed LED circuit.
11.3 APPENDIX 3: PULSE GENERATION USING AN ARGON-ION LASER

Tests of the pyroelectric detector required greater pulse powers than were available using LEDs. An argon-ion laser was used as the source of optical power. A Pockels cell and two linear polarising filters were used to control the blocking or passing of the laser beam. Figure A3.1 shows the arrangement of the equipment. The polariser at the input to the Pockels cell ensured that the laser beam had only a single polarisation. This was rotated for maximum transmitted power prior to use of the equipment. With no voltage applied to the Pockels cell the incident laser beam is transmitted unmodified. Once a sufficient voltage is applied the beam polarisation is rotated, ultimately by 90°. The output polariser was aligned to pass the laser beam only after it had been rotated by 90° and to block it otherwise. It was therefore possible to control the beam power transmitted by the second polariser by changing the Pockels cell drive voltage. A dedicated high voltage amplifier was required to drive the Pockels cell. Before the tests the Pockels cell drive voltage bias and amplitude were adjusted to provide the best optical square wave output (in terms of rise time, flatness of maximum transmitted optical power and blocking of the laser beam in the off condition). It was found under the optimum operating conditions that an extinction ratio (the ratio of power transmitted between on and off modes) of 30:1 could be obtained. The rise time was limited to approximately 1μs and the fall time to 6μs by the high voltage amplifier.

A reflective rotary variable attenuator was used to control the pulse power output from the Pockels cell arrangement. The reflected portion of the beam was monitored using a photodiode and oscilloscope. This enabled the pulse temporal profile to be determined.
11.4 APPENDIX 4: METHOD OF DETERMINING DETECTOR SPATIAL NON-UNIFORMITY

The spatial non-uniformity of detectors was determined using a helium-neon laser with a beam diameter of 0.8mm. The detector under test was mounted on a manually controlled linear transverse slide. Before a test the laser was left for thirty minutes to reach thermal equilibrium to ensure that the power was stable. The laser output power was 2.4mW which was usually reduced to 0.9mW using an optical attenuator. Measurements of the detector output were taken at 0.5mm intervals over the active area of the detector.
11.5 APPENDIX 5: LASER RADIATION INJURY

11.5.1 The biological damage mechanisms of laser radiation

The biological effects of exposure to excessive radiation levels may be divided into thermal, photochemical, thermoacoustic and electrical damage mechanisms. Thermal damage is caused when the absorbed energy heats a cell sufficiently to cause death. The threshold for cell death is a function of temperature and time. Higher temperature elevations can be tolerated for shorter durations [115].

Photochemical damage occurs when the energy of an absorbed photon is sufficient to directly affect the molecular structure of the cell and disrupt cell function. This effect has a threshold energy value, below which the photon energy is insufficient to cause any change. The increase in photon energy at shorter wavelengths means that photochemical effects are regarded as being operative at wavelengths shorter than 550nm [24]. Natural repair processes are capable of compensating for constant low level exposure to photochemically active wavelengths [7], such as ambient ultraviolet. Photochemical damage occurs when the damage by absorbed radiation exceeds the repair capacity of the tissue. Even at short wavelengths where photothermal damage occurs, thermal damage may still predominate. This is particularly so for short exposures in which the instantaneous power is high, but the total energy is low [24].

Thermoacoustic damage is thought to be the limiting factor for very short pulses (10μs to 1ns) where the instantaneous irradiance causes such rapid heating that shock waves are generated as cells rupture [116]. These shock waves cause damage away from the site of radiation absorption. The threshold for this effect in very short pulses is below that for direct thermal damage to cells. At still shorter pulses (< 1ns), thresholds fall below those expected for thermoacoustic damage. It has been suggested that the electric field strengths caused by the high instantaneous powers associated with such short pulses directly cause electrical breakdown of tissue [116].
11.5.2 Factors influencing the occurrence of laser radiation injury

The nature of any injury resulting from exposure to laser radiation is a function of the interrelationship between the damage mechanism and the human factors controlling the exposure conditions. Laser radiation hazards may be regarded as a subset of more general optical radiation hazards. There is no evidence that the monochromatic nature of laser radiation affects the hazard [117]. The most significant factors controlling radiation hazard are the wavelength of the radiation and the duration of exposure to the radiation.

The wavelength of incident radiation is significant in determining the type of injury. Table A5.1 shows the definitions proposed by the Commission Internationale de l'Éclairage (CIE) for division of spectral regions [96]. These divisions are based on the biological effects of different wavelengths and are therefore convenient for hazard assessment purposes.

<table>
<thead>
<tr>
<th>Spectral region</th>
<th>Wavelength Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>UV-C</td>
<td>100 - 280 nm</td>
</tr>
<tr>
<td>UV-B</td>
<td>280 - 315 nm</td>
</tr>
<tr>
<td>UV-A</td>
<td>315 - 400 nm</td>
</tr>
<tr>
<td>VIS</td>
<td>360-400 nm to 760-800 nm</td>
</tr>
<tr>
<td>IR-A</td>
<td>780 nm - 1.4 μm</td>
</tr>
<tr>
<td>IR-B</td>
<td>1.4 - 3 μm</td>
</tr>
<tr>
<td>IR-C</td>
<td>3 μm to 1 mm</td>
</tr>
</tbody>
</table>

Table A5.1: CIE Vocabulary for spectral regions [96]

Ultraviolet radiation usually causes photochemical damage at lower levels than required for thermal injury. Short term overexposure of skin results in erythema (sunburn) [117]. Long term overexposure at lower levels has chronic effects such as an increased risk of skin cancer and premature skin ageing [117]. Ultraviolet damage to the eye is confined mostly to the cornea and lens [116]. The majority of the ultraviolet radiation is absorbed in these structures, especially the cornea. Only UV-A wavelengths may penetrate to the retina to cause damage [115]. Overexposure of the cornea causes the acute effect termed photokeratitis, recovery from the associated damage occurs within a couple of days [116]. Extreme overexposure may cause
permanent opacity of the cornea [115]. Longer wavelength UV-B and UV-A is partially transmitted through the cornea and absorbed by the lens [115]. Acute effects to the lens are only observed at higher exposure levels than corneal damage, corneal damage thresholds therefore control acute injury thresholds [116]. Chronic effects of lenticular overexposure may include premature generation of cataracts and opacities but this is not proven [116]. For the purposes of laser radiation hazard assessment the ultraviolet damage thresholds for skin and ocular exposure are taken to be identical. This neglects the fact that the skin is able to increase its resistance to ultraviolet damage after exposure by tanning and thickening of the outer layers whereas the cornea has no such mechanism.

Wavelengths between 400nm and 1.4μm (VIS and IR-A) have differing damage thresholds for ocular and skin exposure. This spectral region is described as the retinal hazard region, the combined focusing effect of the components of the eye increases the irradiance at the retina by a factor of approximately 100,000 over that at the cornea [115]. Consequently ocular exposure is more hazardous than exposure of the skin. Generally it is not possible to exclude the possibility of ocular exposure and the lower thresholds are used to determine permissible exposures. The predominant damage mechanism within this spectral region is thermal with thermoacoustic and electrical effects becoming significant for short pulses. Within the short wavelength region (550nm to 400nm) photochemical damage to the retina occurs at lower thresholds than thermal damage for exposures lasting between 1s and 1000s [7]. This is termed the blue light hazard region.

The ability of irradiated tissue to dissipate heat is a fundamental control of damage threshold. If the eye is irradiated and radiation is focused onto the retina then the size of the image is significant. Small retinal images can dissipate heat radially and in depth whereas larger images are less able to dissipate heat radially. The temperature rise in the centre of a large image is therefore greater than that of a smaller image. Whole body exposure to laser radiation is uncommon [118] hence it is usual to exclude the effects of heat stress caused by heating of the entire body from the hazard assessment [118].
Longer wavelengths have near identical damage thresholds for ocular and skin exposure [118]. This neglects the more serious effects of corneal injury compared to a skin burn. IR-B radiation does not reach the retina, absorption occurs in the cornea, lens and aqueous humour [115]. For these wavelengths absorption occurs in a significant volume the thermal load is more evenly distributed and damage thresholds for short (<10s) exposures increase [19]. As wavelength increases, the absorption occurs at shallower depths in the eye. For wavelengths longer than 2.6μm it is assumed that absorption is limited to the outer layers of the cornea [19]. This represents a very localised thermal load and gives a lower damage threshold.

The exposure duration is defined by one of two controlling factors. The most fundamental is the time for which the laser operates. Unless the laser emits only a single pulse, applying total operational time would be difficult (the duration of laser operation may vary from day to day), or over-restrictive. Alternative controlling factors are based on the physiological or behavioural factors which may limit realistic exposure durations.
11.6 APPENDIX 6 : LASER SAFETY STANDARDS

11.6.1 Evolution of the laser safety standards

A brief history of laser safety standards is useful to place the current standards in context. The work of Sliney [1,7] provides further information.

Initial standards governing exposure limits were developed by the US Military between 1962 and 1963 in response to the use of rangefinders based on ruby lasers. During the 1960s other standards were developed by industrial organisations, research laboratories and in the UK, the Ministry of Aviation. The majority of these standards covered a small number of specific laser types and exposure durations, limited by the availability of damage information. The resultant MPEs provided a discontinuous set of limits. For example an early British Standard [119] specified corneal MPEs for a 1µs Ruby laser pulse of $3 \times 10^4 \text{ J/m}^2$ if the laser was Q switched, but $1 \times 10^2 \text{ J/m}^2$ for a "long pulsed" laser exposure of the same duration. As the range of available laser types and pulse widths increased this became an unsatisfactory situation.

In addition to the problems of discontinuities in the early MPE values it became apparent that a laser hazard classification was required. An increasing problem was the over zealous application of guidelines for high power lasers (predominantly ruby and Nd-YAG) to much lower power lasers such as helium-neon. An initial subdivision was determined on the basis of the optical hazard presented by a diffuse reflection of the laser beam. It was reasoned that if only the beam was capable of causing injury then the hazard would remain within a local area whereas if a diffuse reflection could cause an injury the area of hazard would be much larger. This was a satisfactory solution whilst lasers were used for research in controlled environments or fully enclosed in industrial applications. Pressure primarily from the manufacturers of low power helium-neon lasers (used in alignment applications) for a less restrictive classification forced change and the introduction of a medium power class. Further classes were then developed to cover low power lasers which were safe so long as natural aversion responses were not overcome (low risk lasers) and low power non-hazardous lasers.
Similar reasoning in the preparation individual standards led to a comparable classification system applying world-wide. Slight differences in thresholds for each class exist, but these are not substantive. A subdivision of the medium power (Class 3) lasers was introduced to better match control measures to hazard and to avoid unnecessary restrictions. Class 3A lasers were defined as being safe for unaided viewing (assuming aversion responses are operative), but being potentially hazardous for viewing with optical instruments. Lasers presenting a hazard for aided or unaided viewing of the beam were defined as Class 3B. American classification standards have also introduced a subdivision of the low risk (Class 2) lasers between those which are not hazardous for an exposure limited by the blink reflex (0.25s) and those which do not present a hazard for exposures greater than 1000s.

In the remainder of the consideration of standards only IEC and the EN derivatives will be considered. These have, with the exception of USA and Canada, world-wide acceptance. Differences between North American and International standards are minor and likely to decrease in the future. The most recent North American standards were brought into greater harmony with International standards [120]. There is no loss of utility in concentrating on international standards and analysis becomes more straightforward as a result.

The original IEC 825 was published in 1984, within the UK it was implemented as BS7192:1989 which was introduced to replace BS4803:1983 (which had replaced BS4803:1972). In 1990 IEC 825 was amended. In this amendment the assessment and classification of pulsed laser sources was changed in line with the latest biological damage threshold data [7]. Hazard control measures for Class 3A lasers were relaxed, some changes to labelling requirements were made and some definitions re-written [28]. CENELEC adopted the amended IEC 825 as EN 60825:1992 with only non-substantive modifications [122].

A second amendment to IEC825 was introduced during 1992. This introduced significant changes and led to the issue of IEC825-1 to replace IEC825. In turn EN 60825-1:1994 was issued. The important changes were an increase in scope to include Light Emitting Diodes (LEDs), relaxation in the exposure limits in the near infra-red
and an attempt to simplify the assessment of extended sources [123]. Modification to
extended source MPEs was required for two reasons; the original approach caused
confusion amongst users and permitted some exposures which could cause injury [20].
Including LEDs within the scope of the standard introduced many problems, with
non-hazardous LEDs being classed as 3B devices. To avoid unnecessary restrictions
on such sources BS EN 60825 was left current, to run in parallel with BS EN60825-1
[124]. Discussion has been under way within the Standards committees to resolve the
problem without excessively relaxing the limits [18,125]. Once this is concluded a
revised BS EN60825-1 will be published.

11.6.2 Current laser safety standards

In the UK the legislative requirement for safety comes from the Health and Safety at
Work Act [126]. Through this Act employer duties are incorporated into statute law
to provide and maintain plant and systems of work that are safe and without risks to
health [127]. A relevant regulation made under the Health and Safety at Work Act to
replace earlier industry specific Acts [127] is the 1992 Provision and Use of Work
Equipment Regulations. British Standards do not have legal force, but it is accepted
that the Health and Safety Executive would use relevant standards in determining
compliance to the general regulations [82,128]. There is therefore a direct relevance

Standard EN60825-1 issued by CENELEC. These are identical to the International
Standard IEC 825-1 issued by the IEC. This group of standards contains three
sections; General (including definitions), Manufacturers Requirements and User's
Guide. Manufacturers' Requirements are based on the need to classify the laser
according to the potential for hazard. Section 3 of the standard; the User's Guide,
introduces the concept of Maximum Permissible Exposures in ensuring that any
exposures to laser radiation do not present a hazard.

The global situation is complicated by the existence of different standards for the USA
and Canada. Two standards are in use in North America; the Centre for Devices and
Radiological Health (CDRH) (part of the Food and Drug Administration (FDA)) issue
a performance standard [38]. The second standard covers user requirements and is issued by the American National Standards Institute (ANSI) [12]. Laser Classification is covered by the CDRH standard, manufacturers must test products and certify compliance with CDRH requirements [121]. Maximum Permissible Exposure Limits are provided by the ANSI standard. Technical differences between International and American standards affect scanned lasers and lasers with strongly divergent beams [119]. There is ongoing effort to homogenise American and IEC standards [120].

Until 1990 the IEC (and therefore CENELEC) produced laser safety standards [122], an EC mandate during 1989 required CEN to develop standards for the Supply of Machinery (Safety) Regulations [129] (commonly known as the Machinery Directive). This introduced a conflict of interest and was mirrored by a similar conflict between IEC and ISO on the responsibility for laser standards. At the end of 1989 a meeting redefined ISO and IEC responsibilities, with ISO taking responsibility for vertical standards and IEC retaining responsibility for the horizontal radiation safety standard [130]. A vertical standard is defined [130] as applying to a specific subject, with safety aspects of this subject calling on horizontal standards. As an example ISO (in parallel with CEN) is producing a standard on the "Safety of machines using laser radiation to process materials" [131]. This cites IEC 825 for all aspects of laser radiation safety related to material processing machines. CEN and CENELEC activities parallel those of ISO and IEC respectively [122].

Other sources of exposure limits to optical radiation exist. The American Conference of Governmental Industrial Hygienists (ACGIH) issue Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices [14]. Within this publication are Threshold Limit Values for lasers over the spectral range 180nm to 1mm, for broad band visible and near infrared radiation between 400nm and 1400nm and for non-laser ultraviolet radiation. MPE values provided by ANSI are equivalent to the TLVs for lasers [14] published by ACGIH [9]. ACGIH also publish a guide for control of laser hazards [9] which covers a subset of the issues addressed by the ANSI standard.
The broad band visible and near infra red TLVs presented by ACGIH are given as weighting functions. These are not directly comparable to laser TLVs because they are only intended to protect against thermal injury and are dependent on the source angular subtense. Laser MPEs make some allowance for photochemical damage below 550nm and generally assume point source exposure. The ultraviolet laser and non-laser TLVs are similar in form with a sharp decrease in threshold between 315nm and 360nm. Laser ultraviolet radiation TLVs are based on straight line approximations to the more complex non-laser curve [116]. At wavelengths shorter than 270nm the laser TLVs remain constant whereas non-laser, corneal TLVs increase (following damage threshold data). For wavelengths greater than 315nm the laser TLVs become independent of wavelength whereas the non-laser TLVs continue to increase. This is explained by the need to avoid thermal damage in the laser case [116]. Exposure Limits for ultraviolet radiation are given by the International Radiation Protection Association (IRPA) [13] but the scope includes incoherent, non-laser sources only. These are identical to the non laser ultraviolet thresholds given by ACGIH.

A wide ranging set of proposals covering protection against the whole range of electromagnetic non-ionising radiation were published on behalf of the EC in 1991 [132]. The aim of this work was to submit to the EC a proposal covering safety requirements arising from the exposures to workers of physical agents. The limits specific to lasers are identical to the MPEs contained in IEC 825 and BS EN60825-1. Concern has been expressed that if the physical agents directive of which this document would be part became law it would have an adverse effect on the development of laser safety standards [122]. MPE values would be set by legislation and could not therefore be readily changed as knowledge of safe exposure limits increases.

Other laser related standards exist, but these do not cover radiation exposure limits. BS EN 31252:1996 (equivalent to ISO 11252:1993) specifies the minimum documentation, marking and labelling requirements for laser devices (but not products incorporating laser devices). BS EN 31253:1996 (equivalent to ISO 11253:1993) defines standard dimensions for mounting hole patterns for attaching external devices (such as flight tubes) around the beam of a laser device. BS EN 60601 covers safety

11.6.3 Application specific laser safety standards

11.6.3.1 Optical fibre communication systems

BS EN 60825-2:1995 [4] (equivalent to IEC 825-2) is specific to the radiation safety of optical fibre communication systems. The standard excludes the use of optical fibre for beam delivery; such applications are covered by BS EN 60825-1. In concept the approach to hazard control is similar to BS EN 60825-1. Engineering and design features to be included in an optical fibre communication system are specified, labelling and administrative controls are described. A radiation hazard classification system is described. The approach to classification is different from BS EN 60825-1 because in normal operation the laser radiation is enclosed and could be classified as a Class 1 product under BS EN 60825-1. Such a classification would not accurately reflect the potential radiation hazard if the system were breached, particularly because control would be necessary over the entire length of the optical fibre communications link. Instead the classification is based on the radiation which could become accessible in "reasonably foreseeable circumstances." These include fibre breakage and accidental disconnection. Hazard levels between 1 and 4 are used, with subdivisions of Hazard level 3 similarly to the classification in BS EN 60825-1. Hazard levels are allocated to parts of the optical fibre communication system according to which AEL of BS EN 60825-1 would be exceeded under reasonable foreseeable circumstances. An amendment is proposed to this standard [133] which provides application notes and examples on the use of the standard.

11.6.3.2 Display lasers

An application specific Guidance Note (PM19) was issued by the Health and Safety Executive covering the use of lasers for display purposes [5]. Leisure and entertainment users are subject to the Health and Safety at Work Act and PM19 was issued to provide guidance. It is now outdated and references MPE and AEL tables from obsolete British Standards. The Guidance Note PM19 is concerned only with
protection against the hazards of laser and collateral radiation and is not concerned with associated laser hazards. Various aspects of the design of the display system for safety are considered. This includes hardware features such as the use of beam stops and siting of controls, and procedural features such as marking of boundaries. Both the AEL for a Class 1 laser and the MPE are used in defining boundaries. It is required in PM19 that the appropriate bodies are notified in advance of the show. In the UK this is the Environmental Health Officer of the local council. Details of the information required in the notification are contained in PM19. In practice the Environmental Health Officer is unlikely to have specific knowledge of laser hazards and will accept the potentially inaccurate information from the display laser company rather than attempting measurement and calculation to verify the safety of the display.

A Technical Report providing guidance for laser displays and shows has recently been issued by the IEC [6]. This document covers the planning, design, set up and conduct of laser displays using lasers exceeding Class 2. The emphasis is on the use for entertainment purposes. Displays of scientific, medical or industrial lasers at trade shows are specifically excluded. IEC 825-1 is referenced for the definitions of laser class and levels corresponding to the MPE.

Three zones are defined by IEC825-3 in terms of the MPE; referred to as the Spectator zone limit (SZL), the Ancillary personnel MPE and the Performer MPE. The fundamental requirement is that the ocular MPE should not be exceeded during normal operation, or under reasonably foreseeable fault conditions. IEC825-3 requires that spectators should not be exposed to radiation exceeding the MPE over all exposure durations including the maximum duration of the display. The blink reflex is therefore excluded as a means of protection for spectators. Ancillary personnel and performers are expected to be aware of laser radiation hazards and not to overcome the blink reflex. A 0.25s exposure duration is therefore applicable to exposure of ancillary personnel or performers. The spectator zone limit is more restrictive than that applying to performers and ancillary personnel as a result of the increased time base.
Vertical and lateral separations between the spectators and regions where the SZL could be exceeded are defined as in PM19. Requirements for planning, set up and checks are covered, with greater emphasis on the need for planning than in PM19. A Display Safety Record (DSR) is required. This is a development of the documentation required by PM19 and includes information on the design, installation and alignment of the display, relevant names and addresses of personnel, regulatory approvals and laser equipment manuals.

11.6.3.3 Other guidance on laser safety

Specific guidance on laser safety in printing was published by the Printing Industry Advisory Committee in conjunction with the Health and Safety Commission [134]. The work provided guidance on the principles for the safe use of laser products with specific application to equipment used by the printing industry. This included printers, copiers, scanners and larger laser equipment such as engraving machines. The now obsolete BS7192:1989 was referenced for information on classification. Engineering controls were emphasised as being important to minimise risk during use and servicing.

A set of guidance notes was published in 1987 by the Committee of Vice-Chancellors and Principals covering lasers [135]. The information was based on the then current standard BS4803:1983 (now obsolete). Consideration is given to the use of lasers in research, teaching and display applications on university premises. The importance of engineering controls is emphasised and responsibility for laser safety translated into the university management structure.
11.7 APPENDIX 7: WAVELENGTH MEASUREMENT TECHNIQUES

11.7.1 Introduction

Laser wavelength is significant for hazard assessment in some situations. The MPE is dependent on laser wavelength in parts of the ultraviolet, visible and near infra-red spectral regions. Some types of detector have a responsivity which is dependent on the wavelength of the incident radiation. This must be known before the incident optical power can be calculated. Manufacturers are required to label all except Class 1 lasers with the emitted wavelength so in many cases the wavelength would be known. The ability to measure the wavelength of the laser radiation would be of value where the laser was not accessible (for example when the laser is built into an entertainment display system). An instrument which could automatically determine the wavelength of an incident laser beam would have the advantage of removing possible transcription errors by the user.

Low cost methods of wavelength measurement were investigated. Instruments such as spectrometers and monochromators could be used for laser wavelength measurement but are prohibitively expensive. Determining the laser wavelength and entering the figure into the instrument is not a difficult task for the user. A wavelength measurement implementation which dominated the overall instrument cost was therefore inappropriate; the value in terms of enhancing the user interface would not match the cost of implementing it.

It was anticipated that wavelength measurement could be implemented within the modular structure of the instrument. A detector head module capable of wavelength measurement is more appropriate than implementing wavelength measurement for every detector head. It is only at visible and near infra-red wavelengths that wavelength measurement is necessary. Alternatively, many users may only intend to make measurements on one or two laser types, or may be confident of knowing the appropriate laser wavelength. The modular approach ensures that such users are not burdened with the cost of unnecessary hardware.
The monochromatic nature of laser radiation means that it is only necessary to identify the wavelength. Performing a full spectral analysis of a wavelength region containing only a single monochromatic laser line implies the acquisition of large volumes of redundant data. It is better to restrict the approach to determining the wavelength of the laser line. This permits the consideration of low cost methods of wavelength measurement.

11.7.2 Suitable wavelength measurement techniques

Several novel methods of wavelength measurement use the variation in absorption coefficient with wavelength of semiconductors, primarily silicon. The intensity, \( p \) of monochromatic radiation incident on a photodiode varies as:

\[
p = p_0 \exp(-A x)
\]

within the diode, where \( p_0 \) is the incident intensity and \( A \) is the absorption coefficient. The absorption depth is defined as \( x = A^{-1} \), at this depth the intensity is 0.37 of the incident intensity [136]. The absorption coefficient, \( A \) is wavelength dependent, decreasing with increasing wavelength.

A commercially available device is suitable for operation between 550nm and 890nm (Silicon Sensor GmbH) and uses a double photodiode structure with the two diodes overlaid. The upper device has a peak of response at short wavelengths whereas the lower device has a peak at longer wavelengths. This is a function of the wavelength dependency of absorption of silicon; the upper device collects photogenerated carriers predominantly at short wavelengths, the lower one becomes more efficient for long wavelengths. By taking the ratio of the two photodiode currents the wavelength of incident monochromatic radiation may be deduced. It should be possible to apply the same structure to an InGaAs device to permit wavelength measurement into the near infrared but such devices are not commercially available.

The wavelength dependent absorption in silicon has been used in different ways by Weling and Malhotra [136] and Wolffenbuttel [137]. Weling and Malhotra use a photodiode fabricated in amorphous silicon. This material has a high concentration of recombination centres, consequently the photogenerated carrier lifetime is short. Only
carriers generated within the depletion layer have a high probability of being collected and contributing to the external photocurrent, others are more likely to recombine. Increasing the reverse bias increases the depletion layer thickness and therefore increases the charge collection efficiency and the photocurrent. The exponential nature of optical absorption means that once the depletion layer depth exceeds the absorption depth the rate of increase in photocurrent falls rapidly towards zero. The approach of Wolffennbuttel is similar; standard silicon is used but the structure of the photodiode is such that only photogenerated carriers absorbed within the depletion layer are collected.

Determination of laser wavelength using these photodiodes is less simple than in the double photodiode structure. It is necessary to measure the derivative of output current with respect to bias voltage. The voltage at which this decreases towards zero is proportional to the laser wavelength. If the laser radiation contained several discrete wavelengths then it might be possible to determine each from the reverse bias voltages corresponding to a decrease in the derivative of output current. As with the double photodiode structure it would be possible to operate at other wavelengths by using a suitable substrate material.

An alternative wavelength measurement method which used the intrinsic spectral response of standard detectors was considered. The idea has common origins with the operation of the wavelength measurement function in optical multimeters [138]. These use coloured glass filters to modify the spectral response of two photodiodes. One photodiode retains a monotonic increase in responsivity with wavelength, the other has a monotonic decrease in responsivity with wavelength introduced by a filter. A ratio of the two outputs permits the wavelength of monochromatic radiation to be determined. Radiation is divided between the two photodiodes using an integrating sphere.

Rather than relying on the spectral characteristics of filters external to the detectors an alternative approach was developed. Photodiodes have an intrinsic variation in responsivity with wavelength and thermal detectors have a near spectrally independent responsivity. A ratio between the output of two such detectors would therefore be sufficient to determine the wavelength of incident monochromatic radiation. Using
intrinsic detector parameters minimises the cost of the system. Operation throughout
the ultraviolet, visible and near infrared spectral regions would be possible by using
appropriate photodiode types. The use of other semiconductor detectors, (whether
junction or photoconductor) would permit operation to 10.6 \mu m if required. So long as
the wavelength remains in the central region of the photodiode response where the
change in responsivity with wavelength is monotonic and below the wavelength of
peak responsivity there is a one to one relationship between wavelength and the ratio
of outputs.

Theoretically the two detector wavelength measurement system could be used on
pulsed lasers. It would be necessary to measure the photodiode output through a low
pass filter which gave the photodiode a similar frequency response to the thermopile.
Changes in the pulse characteristics would then have no effect on the ratio of detector
outputs.

11.7.3 Practical investigation

It was essential that the division of radiation between detectors was spectrally
independent. A silicon photodiode and thermopile were used to verify the concept at
visible wavelengths. An integrating sphere was adopted as the polarisation
independent means of distributing radiation between the detectors. There are various
compromises in the design of an integrating sphere. Integrating sphere throughput
decreases as the sphere diameter increases. The proportion of incoming radiation
reaching each detector decreases. As sphere size decreases, the detectors become a
significant proportion of the sphere wall. A detector acts as an absorber rather than a
diffuse reflector. This reduces the effectiveness of the sphere at distributing radiation
uniformly. The impact of degraded sphere performance is reduced by designing the
sphere so that no detector field of view includes another detector or the point of first
incidence of laser radiation.

A 1.875 inch diameter aluminium sphere was fabricated from two hemispheres. This
diameter was selected to maximise throughput without degrading the quality of the
radiation division. The inner surface of the sphere was coated with Barium Sulphate
paint, known to be a diffuse surface over the spectral range of interest. Holes for the
photodiode and thermopile were drilled into the sphere. Flanges were fixed to these holes to restrict the detector field of view. On the sphere face opposite the detectors a hole was drilled for the incoming radiation. A flange was used to limit the angle of acceptance of the sphere. This arrangement ensured that each detector could only view diffuse wall and was not exposed to radiation which had only undergone a single reflection.

Figure A7.1 shows the results of a transverse scan across the sphere inlet port (5mm diameter) at 514nm with a 1.5mm beam diameter. It is apparent that the response across the port is reasonably uniform, especially when the ratio of photodiode to thermopile output is considered. A tuneable argon ion laser was used to investigate the spectral response of the detector array. The laser power was 30mW. On weaker lines lower powers were used, but to provide a stable output the laser was always operated in "light control" mode. The photodiode output was amplified using a transimpedance amplifier, the thermopile using a voltage amplifier. Gain was selectable in decades for each amplifier. Figure A7.2 shows the ratio of photodiode to thermopile output. Between 514nm and 457nm the ratio changed by approximately 23%, corresponding to an average sensitivity of 0.41% per nanometre. The response curve appears to have two sections with different gradients. At shorter wavelengths the more rapid decrease in responsivity is a consequence of reduced photodiode performance in the blue region of the spectrum. Manufacturer's data for the spectral response of the device shows a similar increase in gradient below 500nm.

11.7.4 Conclusions

The wavelength sensitivity of the combination of a photodiode and spectrally insensitive thermopile was demonstrated by the initial investigation. The disadvantage of the integrating sphere was that the power reaching the thermopile was limited. Noise therefore became significant. This had the effect of reducing the spectral resolution of the system. Using a smaller sphere would have reduced the uniformity with which radiation was divided between the detectors. Thermopile detectivity limitations make the approach better suited to wavelength measurement of lasers with power exceeding 10mW, above the range of interest for hazard assessment.
Alternative radiation division methods could improve the performance obtained with an integrating sphere. Possible alternatives are the use of a beamsplitter plate or a fibre bundle.

A quartz plate beamsplitter is suitable for the ultraviolet, visible and near infrared (transmissive between 200nm and 2μm). It is necessary to use an uncoated plate to ensure that the division ratio is a function only of the material refractive index and therefore predictable over the spectral region. The ratio between transmitted and reflected portions of a laser beam incident on a flat plate beamsplitter has an inherent polarisation sensitivity. This may be minimised by mounting the plate near normal to the incident radiation; the difference in reflection and transmission between polarisations rapidly becomes significant away from normal incidence. The practical problem of this approach is that the reflected beam is only a couple of degrees separate from the incident beam. In order that the detector for the reflected beam does not obstruct the incoming beam the distance between detector and beamsplitter must be relatively large. This makes the angle of acceptance of the arrangement narrow. An alternative is to restrict the polarisation of the incident radiation using a polarising filter. In use it would be necessary to rotate the entire detector assembly for maximum reading. Since the polarising filter would precede the division of radiation the filter
spectral response would be unimportant (so long as the filter remained transmissive). With this approach it would no longer be necessary to keep the beamsplitter near normal to the incident radiation.

A fibre bundle could be used to divide the radiation between two or more detectors. A fraction of the large number of fibres in the bundle would be used to convey radiation to each detector. To ensure that the division ratio was uniform regardless of incident beam diameter or position the division of fibres would have to be random and the fibre diameter would have to be small in comparison to the smallest anticipated laser beam diameter. The spectral transmission characteristics of the fibre would be irrelevant so long as the fibre did not become opaque.

It was apparent that the differing spectral responses of a thermal detector and a photodiode could form the basis of a laser wavelength measurement system. Further development would be required to make a practical system. The integrating sphere was not developed further in the prototype instrument, neither were the alternative radiation division methods investigated. It was felt that the benefit of implementing the wavelength measurement function was not sufficient to justify the cost and time of continuing the investigation.
11.8 PUBLICATIONS ARISING FROM THE RESEARCH


<table>
<thead>
<tr>
<th>Glossary Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorption depth</td>
<td>The depth at which the intensity of radiation has fallen to 1/e of the incident value. [136]</td>
</tr>
<tr>
<td>Accuracy</td>
<td>The degree of correctness with which a measured value agrees with the true value. [139]</td>
</tr>
<tr>
<td>ACGIH</td>
<td>American Conference of Governmental Industrial Hygienists</td>
</tr>
<tr>
<td>AEL (Accessible Emission Limit)</td>
<td>The maximum accessible emission level permitted within a particular class. [3]</td>
</tr>
<tr>
<td>Angular subtense ($\alpha$)</td>
<td>The visual angle subtended by the apparent source (including diffuse reflections) at the eye of an observer or at the point of measurement. [3]</td>
</tr>
<tr>
<td>ANSI</td>
<td>American National Standards Institute</td>
</tr>
<tr>
<td>Beam diameter ($d_J$)</td>
<td>Diameter of an aperture in a plane perpendicular to the beam axis which contains $u$ % of the total beam power or energy. For $u = 86.5$ the indices can be omitted. ($u = 86.5$ corresponds to the $1/e^2$ beam diameter commonly used to specify the output beam diameter of lasers) [57]. A $1/e$ beam diameter is used in hazard evaluation [140].</td>
</tr>
<tr>
<td>Beam positional stability</td>
<td>Maximum transverse displacement and/or angular movement of the beam away from an average, steady state position. [33]</td>
</tr>
<tr>
<td>Blink reflex</td>
<td>An automatic aversion response to bright light, assumed to operate within 0.25s of exposure.</td>
</tr>
<tr>
<td>BSI</td>
<td>British Standards Institution</td>
</tr>
<tr>
<td>Calibration</td>
<td>The set of operations which establish, under specified conditions, the relationship between values indicated by the measuring instrument or output signal of the detector and the corresponding known values of a measurand. [30]</td>
</tr>
<tr>
<td>CDRH</td>
<td>Centre for Devices and Radiological Health (USA)</td>
</tr>
<tr>
<td>CIE</td>
<td>Commission Internationale de l'Éclairage</td>
</tr>
<tr>
<td>Collimated beam</td>
<td>A parallel beam of radiation with very small angular divergence or convergence. [3]</td>
</tr>
<tr>
<td>Confidence level</td>
<td>Probability that a random variable $x$ lies in a specified interval. [106]</td>
</tr>
<tr>
<td>Consistency</td>
<td>See precision.</td>
</tr>
<tr>
<td>Term</td>
<td>Definition</td>
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<td>-------------------------------------------</td>
<td>----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Continuous wave (c.w.)</td>
<td>The output of a laser which is operated in continuous rather than pulsed mode. In the standard, a laser operating with a continuous output for a period equal to or greater than 0.25s is regarded as a c.w. laser. [3]</td>
</tr>
<tr>
<td>Correlation coefficient ($r$)</td>
<td>Measure of how well a curve fits a set of data. A value of 1 indicates a perfect relationship and a value of 0 indicates no relationship. [106]</td>
</tr>
<tr>
<td>Dark current</td>
<td>The current flowing in a detector in the absence of irradiation. [139]</td>
</tr>
<tr>
<td>Detector</td>
<td>A device which transduces radiant power or radiant energy into another, usually electrical, quantity without signal processing or indication. [30]</td>
</tr>
<tr>
<td>Detector head</td>
<td>In this work a detector head is used to describe the combination of a detector and additional signal processing.</td>
</tr>
<tr>
<td>Diffraction limited spot</td>
<td>The minimum diameter of the image formed of a point source by an imaging system, determined by diffraction effects.</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>The ratio between the overload level and minimum acceptable signal level in a system or transducer. The minimum acceptable signal level of a system or transducer is ordinarily fixed by one or more of the following; noise level, low level distortion, interference or resolution level. [139]</td>
</tr>
<tr>
<td>Electromagnetic Interference (EMI)</td>
<td>An electromagnetic phenomenon that may be superimposed on a wanted signal. In a signal transmission path, either extraneous power which tends to interfere with the reception of desired signals or the disturbance of signal which results. [139]</td>
</tr>
<tr>
<td>Elemental error</td>
<td>Individual source of measurement error. [106]</td>
</tr>
<tr>
<td>Errant laser radiation</td>
<td>Laser radiation which deviates from a defined beam path. Such radiation includes unwanted secondary reflections from beam path components, deviant radiation from misaligned or damaged components and reflections from a workpiece. [3]</td>
</tr>
<tr>
<td>Error (measurement error)</td>
<td>The algebraic difference between a value that results from a measurement and the corresponding true value [139].</td>
</tr>
<tr>
<td>Extended source</td>
<td>An extended source of radiation that can be resolved by the eye of an observer into a geometric image in contrast with a point source of radiation which cannot be resolved into a geometric image. [9]</td>
</tr>
<tr>
<td>Term</td>
<td>Definition</td>
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<td>-------------------------------</td>
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<tr>
<td>Fall time constant</td>
<td>The time required for the detector output to fall, after a removal of a steady input, from its initial value to the fraction 1/e of its total change. [30]</td>
</tr>
<tr>
<td>Field of view</td>
<td>The angular extent of object space that can be observed or embraced by an optical instrument. [141]</td>
</tr>
<tr>
<td>Hotspot</td>
<td>Hotspots are defined as localised areas of the beam where the beam irradiance is much greater than the average across the beam. [1]</td>
</tr>
<tr>
<td>Instrument</td>
<td>In this work the term instrument describes the combination of a detector head and meter.</td>
</tr>
<tr>
<td>Intrabeam viewing</td>
<td>All viewing conditions whereby the eye is exposed to laser radiation, other than extended source viewing. Examples are viewing of collimated beams and of point sources. [3]</td>
</tr>
<tr>
<td>Irradiance</td>
<td>Quotient of the radiant flux dΦ incident on an element of the surface by the area dA of that element. [3]</td>
</tr>
<tr>
<td>Johnson Noise</td>
<td>The noise caused by thermal agitation (of electron charge) in a dissipative body. The noise power is equal in all equal frequency increments. [139]</td>
</tr>
<tr>
<td>Light Emitting Diode (LED)</td>
<td>Any semiconductor pn junction device which is designed to produce electromagnetic radiation by radiative recombination in a semiconductor in the wavelength region 180nm to 1mm. Radiation is produced primarily by the process of spontaneous emission, although some stimulated emission may be present. [3]</td>
</tr>
<tr>
<td>Limiting aperture</td>
<td>The circular area over which irradiance and radiant exposure shall be averaged. [3]</td>
</tr>
<tr>
<td>Maximum Permissible Exposure (MPE)</td>
<td>That level of laser radiation to which, under normal circumstances, persons may be exposed without suffering adverse effects. The MPE levels represent the maximum level to which the eye or skin can be exposed without consequential injury immediately or after a long time and are related to the wavelength of the radiation, the pulse duration or exposure time, the tissue at risk and, for visible and near infra-red radiation in the range 400nm to 1400nm, the size of the retinal image. [3]</td>
</tr>
<tr>
<td>Meter</td>
<td>In this work the term meter is reserved for the part of an instrument used to display the signal from a detector head. The meter may permit functions to be performed on the signal from the detector head.</td>
</tr>
</tbody>
</table>
Nominal ocular hazard distance (NOHD) The distance at which the beam irradiance or radiant exposure equals the appropriate corneal MPE. If the NOHD includes the possibility of optically aided viewing, this is termed the extended NOHD. [3]

Point source Ideally, a source with infinitesimal dimensions. Practically, a source of radiation whose dimensions are small compared with the viewing distance. [9]

Precision The quality of coherence or repeatability of measurement data, customarily expressed in terms of the standard deviation of the extended set of measurement results from a well defined measurement process in a state of statistical control. The standard deviation of the conceptual population is approximated by the standard deviation of an extended set of actual measurements. [139]

Precision errors Non-repeatable errors due to unknown and/or uncontrollable factors influencing the measurement. [134]

Precision index (S) The sample standard deviation of a set of measurements. [106]

Precision limit Estimate of the precision error for the measurement of a variable based on the precision index of a small sample of measurements of the variable. [106]

PSpice A computer program used for simulation of electronic circuits.

Pulse duration The time increment measured between the half power points at the leading and trailing edges of a pulse. [3]

Pulsed laser Laser which delivers its energy in the form of a single pulse or a train of pulses. The duration of the pulse is less than 0.25s. [3]

Radiant energy Time integral of the radiant flux over a given duration Δt. [3]

Radiant exposure At a point on a surface, the radiant energy incident on an element of a surface divided by the area of the element. [3]

Radiant flux (radiant power) Power emitted, transmitted or received in the form of radiation. [3]

Reduced single pulse MPE The MPE for a single pulse in a train of pulses.

Repeatability The maximum observed difference in a series of replicated or repeated measurements [106].
<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
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<tbody>
<tr>
<td>Repetition (repeated measurements)</td>
<td>Repetition of a measurement to determine the uncertainty implies that measurements are taken over a short period of time. [106].</td>
</tr>
<tr>
<td>Replication (replicated measurements)</td>
<td>Replication of a measurement to determine the uncertainty requires that measurements are taken over a significant period of time in order that all random effects may be manifested [106].</td>
</tr>
<tr>
<td>Response time constant (rise time)</td>
<td>The time required for a detector output to rise from its initial value to (1-1/e) of its final value when a steady input is instantaneously applied. [30]</td>
</tr>
<tr>
<td>Responsivity</td>
<td>Quotient of the detector output quantity Y by the detector input quantity X. [30]</td>
</tr>
<tr>
<td>Single fault condition</td>
<td>Any single fault that might occur in a product, and the direct consequences of that fault. [3]</td>
</tr>
<tr>
<td>Systematic error</td>
<td>Repeatable error in a measurement which does not vary with replication. [106]</td>
</tr>
<tr>
<td>Transimpedance amplifier</td>
<td>An amplifier generating a voltage output for a current input.</td>
</tr>
<tr>
<td>Uncertainty</td>
<td>Estimation of error in a measurement or result, usually determined with a certain level of confidence [106]. (95% confidence level is specified by BS EN 61040 [30].)</td>
</tr>
</tbody>
</table>