A Risk Assessment Methodology for the Use of Lasers in the Entertainment Industry

by

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ABSTRACT

Lasers have been used in the entertainment industry since 1964, when they were used in the film Goldfinger. Laser display shows commenced in about 1973. It would be reasonable to expect laser safety to have been adequately addressed over the last twenty-five years. This research showed that the industry was not able to assess the risks from its work. A national survey of the competence of enforcing officers showed that they rarely had the necessary expertise to judge the safety of shows. Therefore, there was often a wide gulf between the laser companies and those responsible for enforcing entertainment and health and safety legislation.

A hazard assessment methodology has been developed which considers any laser show as a series of modules which may have different hazards associated with them at different stages of the life cycle, and different people would potentially be exposed to these hazards.

A number of laser radiation exposure situations have been assessed, including audience scanning. A theoretical understanding of the laser scanning issues and the application of measurement techniques to enable assessments to be carried out against internationally recognised maximum permissible exposure levels were developed. The conclusion was that the practice of audience scanning was not acceptable in its current form. A number of laser companies worldwide have accepted this view as a direct result of this research.

A means of presenting the risk assessment for a laser display has been developed which provides benefits for the laser company, the venue manager, event promoter and the enforcing officer. It is recognised that a complete assessment may not be possible in the time available and a focused approach to the assessment is presented. In summary, if audience scanning is intended, the assessment is complex, but if this practice is not intended then the assessment can be straightforward.

Suggestions are made for applying the risk assessment methodology to other laser applications.

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Finally, and most importantly, I thank my family. Without the unfaltering support of my wife, Jacqueline, I could not have hoped to embark on such a venture. Our young children, Robert and Isobelle, have grown to accept that their father has many places of work - NRPB, Loughborough, the study at home, nightclubs and fields waiting for laser displays to commence. I hope this research goes some way to ensuring that, when they get to the age of wanting to attend such events, their safety will be assured.

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1. General Introduction

1.1 Introduction

Laser radiation was first demonstrated practically by T H Maiman in 1960 using a pink ruby crystal (Maiman 1960). Since then many materials have been made to exhibit laser characteristics. The number of laser applications continues to increase every year. High radiant power lasers and those which utilise chemicals can present special hazards, such as the effects of fumes from the laser/workpiece interface, high voltages and carcinogenic properties of the chemicals. In many applications the laser radiation is contained by engineering design making the 'associated hazards' more important in safety terms. However, there are a number of applications where, because of the function of the application, laser radiation is accessible. These applications include the use of lasers for guidance systems for military uses, research and development, medical applications, alignment work within the construction industry and for display and entertainment.

The largest number of people potentially at risk from laser radiation are those who attend events where lasers are used for display and entertainment. The applications range from hand-held laser pointers used in lecture theatres, where the audience may consist of, say, five to a hundred people, to open air events using multi-watt lasers where the audience may run to tens of thousands.

Apart from the actual use of lasers for entertainment, by the use of beams onto screens or into the air, the display of laser products at, for example, trade exhibitions, may also present risks (from exposure to laser radiation and other agents) which may not have been envisaged by the designers of the product.

The audiences attending laser displays will cover all age-ranges and social groups. Nightclubs and discotheques will appeal to the age range from 16 to about 30. Live music will cover the complete age range, although rock and pop music tends to appeal to audiences from about 12 to 30 years. Classical music and particularly open-air concerts can cover the whole age range. Laser displays may also be included in pleasure parks which will attract family groups. The average family tends to assume that their safety is assured when attending any event aimed at them. There is a belief that "they", whoever they may be, will have taken all reasonable measures to provide a safe show. This assumption cannot necessarily be applied to some uses of laser displays in, for example, raves. Here the element of risk, with the possible availability of drugs, is potentially the attraction. The research here is primarily concerned with the safety of the family group although, of course, the same safety principles should always apply. However, the balance of risk may be less clear in some areas.

In the United Kingdom guidance on the safety aspects of lasers used for entertainment and display is promulgated by the Health and Safety Executive. Until October 1996 this was PM19 (HSE 1980). This states that the maximum permissible exposure levels (as specified in the American National Standards Institute publication ANSI Z136.1 (1976)) should not be exceeded for the public or for a height up to 3 m above where the public can stand and 2.5 m to any side of where they are permitted. The author has been involved with a number of display companies in his capacity as one of the National Radiological Protection Board's laser safety advisers. The standard of knowledge of the laser operators gives some cause for concern. Their appreciation of the safety aspects, relevant safety standards and guidance, measurement and calculation methods is limited. It also appeared that this lack of knowledge also extended to the enforcing authorities. This prompted the research reported here. During the course of the research, input has been provided to the development of new guidance.

1.2 Historical Perspective

The laser's first involvement with the entertainment industry was probably in the James Bond movie Goldfinger which was released in 1964. The laser appeared to be a helium-neon laser emitting a red beam and was allegedly cutting gold, something that is extremely difficult even now with high power industrial lasers. Safety issues were immediately raised in this application since the implication was that James Bond was about to be cut in two by the laser radiation.

The artistic features of visible laser beams were recognised, especially the naturally low divergence, brightness and unique speckle pattern when reflected from matt surfaces

(Hecht 1992). The first actual laser show is believed to have taken place in Los Angeles in 1973 (Hecht 1978). A review of the early years of lasers in art and entertainment can be found in Kallard (1979).

The rock group The Who are generally recognised as pioneering the integration of the laser effects with music. John Wolff provided The Who with a few 90-second bursts of laser light from eleven lasers during their performances (Kallard 1979). By 1977 Genesis were using lasers on their world tour (Brockum International 1977) and Tangerine Dream were touring with LASERIUM from Laser Images Inc. Tangerine Dream's tour brochure for 1978 specifies a 22 W Spectra Physics double-ended argon laser (Concert Publishing 1978). Today lasers are commonly used for entertainment either as stand-alone presentations or accompanied by music, which may be recorded or live. Systems may be very sophisticated and computer controlled or may be second-hand lasers and hand-held mirrors. The technology is discussed in Chapter 4.

The use of lasers for entertainment would initially have involved the combined expertise of artists and scientists. Lasers were initially constructed and operated by people who should have been aware of the safety issues. If they were not aware then they were likely to be injured or killed. It may be reasonable to assume that the knowledge of safety issues would have passed from the scientists to the artists but there is little evidence for this. The pioneering applications of lasers for entertainment do not appear to have involved direct exposure of people (the audience) to the laser radiation. This practice only appears when the capability to move laser beams around was developed, some time in the early 1970s. HOLOCO certainly should have had the capability to assess the safety of their early laser shows (Wolff *et al* 1977) but do not seem to have done so.

Laser games have become popular in the 1990s. Several systems are used in the UK but they are all based around a 'gun' containing a laser emitting visible radiation coupled with an infrared diode which is used to communicate with target areas. This application of lasers for entertainment is unique in that it can reasonably be expected that untrained members of the public will be intentionally targeting other members of the public with laser radiation.

The original aim of this research was to consider modes of failure which would result in audience exposure to the laser radiation. However, it became obvious that the audience were routinely exposed to laser radiation - so-called audience scanning. The next stage was to consider modes of failure which would result in audience exposure at levels in excess of the maximum permissible exposure (MPE) levels. An understanding of the techniques used to generate scanned beams and the development of instrumentation which could measure them was essential.

There was naturally an initial reluctance on the part of the laser display companies to any external influence on their, extremely competitive, business. However, it became clear to a number of the larger display companies who wished to work towards a greater understanding of the risks associated with their activities that there was an element of commercial interest in wanting to be able to claim that their shows were 'safe'.

The research has been a process of mutual learning. The laser companies have been very open about the displays they produce. The enforcing officers have equally been very open about the practical issues of assessing these displays.

January 1997 saw the formation of a professional body for the laser entertainment industry. This was triggered by the presentation of, amongst other things, the findings from this research.

There is no doubt that education and training will be a major part of the development of this industry in the future. This will not only apply to the laser companies themselves but also to the laser system manufacturers, the venue managers, the promoters and also the enforcing officers.

1.3 Summary

Lasers have been used in entertainment for over thirty years and in light shows for about twenty-five years. The initial applications would have involved collaboration between scientists and artists. Safety should have been part of the normal working practices from the beginning.

The development of turn-key laser systems would have taken the scientist out of the laser entertainment framework. The use of lasers to scan audiences should have triggered questions on the safety issues. The laser entertainment industry would be working alongside other entertainment professionals who would be facing many of the associated hazards from the use of lasers. However, there is specific guidance on laser radiation hazards in entertainment but nothing which considers the other hazards.

Family groups attending events using lasers expect their safety to be assured. Ideally this requires the laser event to be staged in a professional and safe manner, which stands up to audit. The fall-back position should be enforcement of safety both within the management of the event and the venue, and the legal framework.

1.4 Aim of the Study

The aim of this study was to determine the status of laser safety in the entertainment industry and identify a methodology for assessing the risks. In particular, the following issues needed to by studied:

- current legislation, guidance and standards, and knowledge and compliance with these;
- differences of approach by the industry and enforcing officers;
- common safety issues;
- whether a methodology could be developed which would be useful to all parties;
- whether specific risks needed to be quantified.

The results from the assessment may not be restricted to the entertainment industry and therefore the application of the research to other laser applications will be investigated.

1.5 Research Methodology

An outline of the methodology for the research to achieve the aims in section 1.4 is presented below.

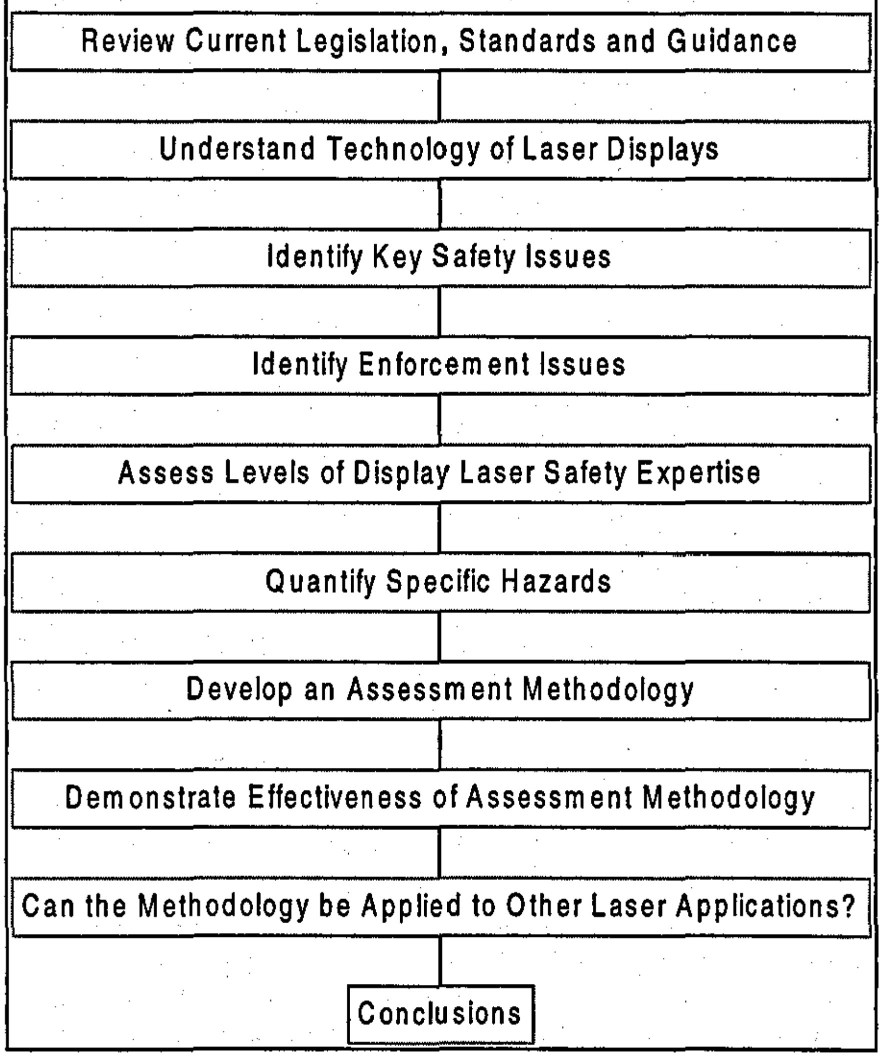


Figure 1.1 Research Methodology

2. Literature Review

2.1 Introduction

As has already been stated in the Introduction, the laser is approaching forty years of age and has been used in entertainment for almost as long. It would be reasonable to expect that guidance, either official or from the industry, would be available to address the safety issues. In practice, the guidance is limited. This chapter reviews the implications of guidance which is available, how these have built on formal standards, and the legal issues in the UK and elsewhere. Of particular concern is how any published material assists those staging laser events, those who promote or host such events, and the enforcing authorities to assess the risks from the use of lasers.

2.2 Laser Entertainment Guidance

There are few specific guidance documents relating to the use of lasers in the entertainment industry. UK guidance is described in this section along with guidance from elsewhere in the world.

2.2.1 Guidance Note PM19

The official guidance on the use of lasers in the entertainment industry in the UK until October 1996 was PM19, published by the Health and Safety Executive in December 1980 (HSE 1980). Since this document was published about seven years after the first laser show in the UK it would be reasonable to expect it to have addressed many of the safety issues. That the document remained the only formal guidance document for sixteen years would also suggest that it must have been successful.

Many of the guidelines in PM19 are derived from statements made by the US Bureau of Radiological Health in 1977 and 1978 (Sliney and Wolbarsht 1980). These statements required that anyone putting on a laser display should be considered a manufacturer of a laser product. The US Federal Product Compliance Standard, 21CFR1040.10 (FDA

1976), required that only class I or class II laser products may be sold as "demonstration laser products". In order to use a laser product of a higher laser class, it was necessary to have a "variance" from the requirements of 21CFR1040.10 having met a number of criteria. These criteria were transferred to the requirements of PM19 and include a requirement for the accessible emission limit for class I (termed class 1 in PM19) not to be exceeded where the audience is to be seated or standing. Separations of 3 m vertical and 2.5 m laterally also come from the US guidance, for supervised performances.

The most important part of PM19 is the requirement for the operator of any display laser product to provide health and safety enforcement officers with "sufficient information, sketches, calculations, radiometric measurement data, etc, to demonstrate that the system can be used safely and without risks to health". This shows that the requirement for a risk assessment has existed in UK guidance since 1980. Irrespective of the content of the remainder of the guidance, this should have provided clear guidance of what was required to meet the general requirement for risk assessment under the Health and Safety at Work etc Act 1974 (HMSO 1974) and the later Management of Health and Safety at Work Regulations 1992 (HMSO 1992).

Another key to the pedigree of PM19 is the reference to the US ANSI Standard Z136.1 (ANSI 1976) for maximum permissible exposure (MPE) and accessible emission limit values. The laser classification scheme was not introduced into the UK until the adoption of the British Standard BS 4803: 1983 (BSI 1983). However, the ANSI standard was updated in 1979 and it introduced further guidance on laser displays, including guidance on the time base to be used. This is still contained in the current ANSI Standard (ANSI 1993), which states in 4.5.1 that "the applicable MPE may be determined by using the classification duration defined as the total combined operational time of the laser during the performance or demonstration within any single period of 3 x 10^4 seconds".

The failings with PM19 are generally through omission. It appears to be assumed that laser radiation will not be scanned across the faces of members of the audience, so-called audience scanning. At least there is no indication of how such an assessment should be carried out. A strict application of the guidance given would be that a scanned beam should be analysed on a single pass of the beam across the eye, with no account taken of repeated exposures.

Appendix 3 of PM19 provides a suggested proforma for presenting the necessary information to the enforcing officer. These tended to be completed by laser display companies to varying degrees, but most followed a generic pattern, thought to originate from one or two longer standing laser display companies. At the start of this research it was considered that the information supplied was too generic to be meaningful. However, it was recognised that an enforcing officer presented with the minimum information may consider the information was meaningful without fully understanding the technical and safety issues. Viewing one Appendix 3 proforma in isolation would not easily identify the lack of specific information about a particular event.

PM19 only covers laser radiation. The other safety aspects, such as fire, explosion, electric shock, etc, are only mentioned in passing in the introduction.

2.2.2 Guidance Note HS(G)95

PM19 was replaced by a further publication from the Health and Safety Executive in October 1996, HS(G)95 (HSE 1996a). This document is specifically titled to only include laser radiation. HS(G)95 is intended to be a goal-setting document with little specific guidance on how to achieve these goals, as is the current climate of UK legislation and guidance. The guidance again stresses the need for risk assessment and clearly sets down the requirements for this through from the designer of the equipment to the laser operator.

Examples of equipment are given in HS(G)95 to illustrate specific points. However, some of these have not been thought through. For example, an example of an external optical component is given as a mirror mounted on a wall bracket using a ball joint. Such devices are generally subject to severe vibration and most products would now be expected to have no vertical movement by design such that the mirror mount, even if it becomes loose, does not tilt the beam down into the audience.

The guidance is now set in terms of maximum permissible exposure only, which is more logical, rather than referring to the classification of the laser display.

Audience scanning is considered, and recognised as a high risk activity by the requirement to have supervision. Chapter 4 of the guidance considers an Installation Safety Assessment. Several pages are dedicated to the issue of audience scanning, although there is no practical guidance on how to actually carry out the assessment. A lot of emphasis is placed on scan failure systems. An interesting footnote at the bottom of page 8 states "HSE recognises that measurement down to the applicable MPE and of scanned emissions may be impracticable". This demonstrates a complete lack of understanding of the measurement issues and the technology available to undertake the assessments.

There are a number of questions which need to be asked about this replacement to PM19. Is it better? In many ways it is, because it does include some more background information, but that does not mean it is more helpful for either the laser company or the enforcing officer. Discussions with both parties suggested that they preferred specific guidance so that a consistent level of enforcement could be expected across the UK. Does it provide practical guidance on risk assessment? No, it gives some pointers but again no practical guidance. Probably the most significant omission from HS(G)95 compared with PM19 is the requirement to notify the enforcing authority. In an ideal world, with self regulation of the industry, this would not be necessary. However, an indication that such notifications are not necessary may mean that laser displays may take place without the necessary safety management and control needed to ensure that they are carried out with the minimum of risk to the public.

2.2.3 Non-UK Guidance

There are a small number of guidance documents issued by other countries. Laser Light Show Safety - Who's Responsible (FDA 1986) published by the Food and Drug Administration (FDA) in the US provides some background information on lasers and hazards, but only mentions the laser radiation hazard. It covers the Government requirements, mainly in terms of requiring a variance from the FDA to operate laser displays. Mention is made of possible additional State and local requirements. There is nothing in the document to explain what a laser show is, nor is audience scanning covered.

The FDA have also issued a number of documents aimed specifically at their inspectors. Examples include the Compliance Guide for Laser Products (FDA 1985) and the Analysis of Some Laser Light Show Effects for Classification Purposes (FDA 1979). Appendix B of the former document includes a statement on Clarification of Certain Laser Light Show Requirements. This includes audience scanning and scanning safeguards. The statement recognises that scanned laser radiation with a peak power in excess of 5 mW has an acute risk of injury if it were to slow down or stop. No account appears to be taken of the effect of multiple pulses as the laser radiation is scanned. Scanning safeguards are considered a "critical performance feature" for high power laser shows. The statement does recognise that, at the time of issue, the FDA had "not received data to show that any scanning safeguard system is adequate for audience scanning".

The second document includes a number of calculations of laser light show effects using galvanometer scanning systems. It includes sawtooth, triangular and sine wave drive signals, all generated from analogue sources. The assessments consider time bases for the duration of example effects and compare the energy into a 7 mm aperture with class I accessible emission limits. However, no consideration is taken of multiple pulses as the beam is repeatedly scanned across the eye.

On 13 December 1979, the Health Protection Branch of the Health and Welfare Canada issued guidance (Morrison 1979) which appears to be based on the FDA recommendations of 1978, and therefore is similar to PM19.

The National Health and Medical Research Council of Australia issued a Code of Practice for the Safe Use of Lasers in the Entertainment Industry in 1995 (NHMRC 1995). This is one of a pair of documents published at the same time, the other one covering the use of lasers in schools. The approach taken in the two documents is similar, even though the intended targets are so different. The Code of Practice only considers the laser radiation issues, although the reader is referred to other Australian documents for cryogenic coolant and high voltage safety. Annexe B provides a flowchart for the recommended alignment procedure. The procedure described suggest that the author has little or no practical experience of a laser light show installation, being more appropriate for a laboratory environment than an entertainment venue. Annexe C recommends a proforma for a Display Safety Record. This requires an assessment of the hazards but does not consider the risks having assessed the hazards.

2.2.4 Summary of Entertainment Laser Guidance

The number of documents available for specific guidance on the safe use of entertainment lasers is small. All concentrate on the laser radiation aspects, with no guidance on non-radiation hazards. Although a requirement for risk assessment was included in the 1980 UK guidance (PM19) this has not been practically addressed. There is clearly the potential for conflict between laser display companies and enforcing officers where guidance, such as HS(G)95, uses a goal-setting approach. The means for achieving the goals rely on an understanding of both the laser safety issues and the practical aspects of laser displays.

Most other countries appear to have no guidance on the safe use of laser displays. Only the US, Canada and Australia have issued guidance. These all suffer the same deficiencies as the UK guidance.

2.3 General Entertainment Guidance

If no practical specific guidance is available for laser display companies then there may be general guidance aimed at the entertainment industry which fills the gap. This is reviewed for the UK. The documents include formal guidance from government, professional association guides and books aimed at the industry.

2.3.1 Fire Precautions Guide

In 1990 the Home Office/Scottish Office published a guide covering fire precautions in entertainment venues which was revised in 1994 (HMSO 1994a). Lasers are covered in three paragraphs (11.40 to 11.42). The first paragraph introduces the laser and the hazard potential. The second paragraph states that certain lasers can present a fire risk and states that licensees should ensure that lasers should be installed and operated by experts although it does not give any guidance to the licensee on how he is to determine the level of expertise. The final paragraph refers to PM 19 and BS 4803: Part 3 (assumed to be the 1983 edition). The publication of a revised standard, BS 7192: 1989 (BSI 1989), was not considered when the document was revised for publication in 1994. However, the Introduction states that the current version of any British Standard should be used.

The guide has no statutory force but it does state (paragraph 6.51) that no lasers should be installed or used without approval. This approval is defined as approval in writing by the licensing authority. An obvious omission is that the guide does not define what the licence is for. It can be assumed that the reference is to the entertainment licence. The legislation concerning entertainment licensing will be considered later.

2.3.2 Pop Concerts Guide

The Health and Safety Commission, the Home Office and the Scottish Office jointly published a guide which has become known as either the Pop Guide or the Purple Guide on account of the colour of its cover (HMSO 1993). The guide has a very practical approach to the safety aspects of events involving large groups of people. It covers management and planning of events, two aspects that do not appear to feature highly in many events involving lasers.

Appendix 1 covers the legal aspects of putting on a pop concert. Three paragraphs are devoted to the legal requirement to undertake a risk assessment and a degree of practical guidance is provided. This is a six step process which covers identifying the hazards through to safe systems of work and review. However, the guidance is not detailed enough for anyone needing to carry out a risk assessment for the first time and by hiding the requirement in an appendix, the implication is that such as assessment is not part of the main management function.

Chapter 10 of the guide covers special effects and pyrotechnics and includes lasers. Reference is made to the then guidance, PM19 and the expected revision HS(G)95.

The requirement for a laser safety officer (LSO) is discussed in paragraphs 10.6 and 10.7. The code suggests that the LSO could be an external consultant. Handover documents are mentioned in 10.7 and 10.8. The closest that laser companies normally get to these are the appendix 3 forms from PM 19. Paragraph 10.8 suggests that the handover document "should contain a detailed specification of the intended scope of the display and the operator should not deviate from that specification. The document should be specific to the venue where the laser display is to occur and should include a drawing of the laser display area in both plan and elevation. The positions of laser sources, mirrors and target areas should be clearly marked, along with the relevant distances and dimensions. The licensing authority will normally ask to see a copy of the handover documents". The onus appears to be placed on the licensing authority to ask for any documentation relating to the laser display, rather than such information being provided up front as required by PM19, and perhaps represents the views of the Health and Safety Executive which were eventually introduced into HS(G)95. Documentation as specific as that suggested here is extremely rare, even for permanent laser installations.

2.3.3 National Outdoor Events Association

The National Outdoor Events Association (NOEA) have published a comprehensive code of practice covering many aspects of outdoor events "other than Pop Concerts and Raves" (NOEA 1993). Members of NOEA are expected to comply with the code of practice but it is also intended for "Organisers (who will know what they can expect to receive), the Suppliers (who will know what they are expected to provide), Inspecting Officers (who will receive clear guide lines and check lists) and all members of the trade associations connected with the Industry (who will then monitor the performance of its members in these activities)".

This code starts with risk assessment and provides suggestions for categories for hazard, risk potential, event type and attendance group. However, the code does recognise that simple assignment of numbers to each of these categories may not be adequate and full detailed assessments may need to be carried out to satisfy all legal requirements.

Laser are defined as "high intensity lighting or strobes arranged for displays". The section on lasers comes within the Electrical chapter. It is interesting that the electrical hazards are considered first. The code requires the installation to be carried out by a "competent engineer skilled in this particular field of operations". The code goes on to say there may "exist non-electrical risks such as radiation or the induction of epilepsy from such equipment". The code refers to PM 19 and to a loose-leaf annexe accompanying the code. The description of the laser classification system is misleading: particularly classes 3A and 3B appear to have been combined into one class and the description is more appropriate to class 3A. The annex refers to BS 7192: 1989 (BSI 1989), although BS EN 60825: 1992 (BSI 1992) was available at the time of publication.

2.3.4 Institute of Lighting Engineers

The Institution of Lighting Engineers (ILE) produced a code in 1995 which included lasers (ILE 1995). The code was produced by a panel with major input from one of the laser display companies. As such, much of the organisational and technical content is quite good. However, there are some basic misunderstandings of the real personnel exposure situations and the risks involved. In particular, the document considers that calculations in support of risk assessments are inaccurate and should only be used when measurements are not possible. However, there is no specific guidance on how the measurements should be carried out. A worrying suggestion is that laser power meters should be used. It is unlikely that these would respond correctly to a scanned laser beam.

2.3.5 Focal Guide

The Focal Guide to Safety in Live Performances (Thompson 1993) considers many safety issues relating to events where lasers are likely to be used. Although the book starts with a chapter on "Safety, Risk and Hazard" this is not followed through into practical guidance.

Advice is presented on the associated hazards from laser events, such as staging, electricity, fire, smoke machines and audience management. A chapter is dedicated to lasers which includes a cursory introduction to laser entertainment technology. When considering the safety evaluation of scanned laser effects, it is assumed that high speed scanning is acceptable for high power lasers provided adequate scan-fail detection and control systems are incorporated. No account appears to be taken of the multiple exposure situation under such scanning conditions. Laser classification is described and it is difficult to see what this achieves since most lasers used in the entertainment industry have the potential to cause eye injuries, ie they are class 3B or class 4. It would have been more appropriate to consider the maximum permissible exposure alone.

2.3.6 Summary of General Entertainment Guidance

The official and industry general guides to safety in the entertainment industry address many of the issues which are common, such as management and planning. However, risk assessment, although introduced is not covered in any detail. Lasers are introduced in each of the guides but generally reference is made to the specific UK laser guidance documents. The advantage of these broader guides is that they address many of the safety issues associated with the use of lasers which are not covered in the specific laser guidance, such as electricity, fire and manual handling. However, the practical guidance on risk assessment appears to be no further developed for these sections of the industry than it is for the laser radiation.

2.4 Laser Safety Standards

Reference has been made to the accessible emission limits and maximum permissible exposure (MPE) levels for laser radiation. These are tabulated in Standards. The MPE levels are derived from experimental data, essentially comparing the effect on the eye or skin with various quantities of laser radiation incident on the respective organ. Some data also comes from incidents involving accidental exposure of people to laser radiation.

The first fully reported laser injury occurred in February 1964 (Rathkey, 1965) when a student in Oregan, USA, received an eye exposure from a ruby laser pumped with an argon flash lamp. However, the biological research into potential eye injuries had been started some years earlier. Zaret *et al* (1961) reported experimental results on 'optical maser' exposures of rabbit eyes in 1961. The radiant exposure levels used for the experiments was 2 x 10^4 greater than the current value for the maximum permissible exposure (BSI, 1994). The authors compared the results with effects produced after exposure to the optical radiation from atomic bomb explosions.

Laser Focus World published an account by Decker (1977) which graphically describes what it is like to receive an injury from a laser. Decker was not wearing goggles, which were available, when he received a 6 mJ, 10 ns pulse from a neodymium:YAG laser operating at 1064 nm. Although his vision was not lost completely in the exposed eye, he continued to have numerous floating objects in his field of view.

McKinlay and Harlen (1984a) reviewed the damage mechanisms over the different wavelength regions (ultraviolet, visible and infrared radiations). In a companion paper (McKinlay and Harlen, 1984b) they compared the threshold injury data with maximum permissible exposure (MPE) levels in the laser standards. They concluded that the MPEs were adequate to ensure the protection of most people. However, they did raise the question of exposure to blue laser radiation producing minimal photochemical repairable lesions. They suggested caution if such exposure is prolonged.

Mellerio (1991) summarised the interaction mechanisms for optical radiation and the potential for damage. Photochemical, thermal and ionisation mechanisms are considered.

Pleven (1986) and Bandle and Holyoak (1987) have published reviews of known laser injuries. In the first report, fourteen accidents in research environments were reviewed which occurred between 1973 and 1986. Most of these occurred in France. Pleven's main conclusion was that although the accidents could have been prevented, there was concern at the ignorance of clinicians in dealing with the injuries. Over fifty cases are reviewed in the second paper: none from the UK. Although most of the accidents relate to radiation damage to the eyes, references are also made to fatal electric shock and radiation induced fires in medical applications.

Rockwell (1997) has reviewed laser accidents over the thirty two years from 1964 to 1996. The Rockwell Laser Industries (RLI) database covers 330 events of which 241 were eye incidents (220 resulting in eye injuries) and 89 related to skin or non laser beam incidents, discussed below. Eleven of the eye incidents involved laser show operators and 16 spectators although the details of the incidents are not reported. These represent 3.3 and 4.9% of the incidents in the database, respectively.

All of this data is used as input to make recommendations on MPE values. The MPE values can then be used to determine accessible emission limits (AELs) which consider the level of laser radiation people can be exposed to having made a number of assumptions, such as control measures. This is the basis of the laser classification scheme widely used throughout the world.

2.4.1 British Standards

Laser safety standards have evolved since soon after the laser was first successfully demonstrated. These standards have been applicable to all laser applications, including laser displays. They are intended to lay down manufacturing standards for laser products and include tables of maximum permissible exposure (MPE) levels for the two critical organs, the eye and the skin.

The development of the MPE level with the development of British laser safety standards can be followed to determine if the level has changed significantly since the first standard was published in 1964 (Ministry of Aviation 1964). The corneal MPE values are summarised in table 2.1 for a visible laser beam for a single exposure to a pulse of 0.01 s, an accidental exposure to a continuous wave (cw) beam assuming the natural aversion response of 0.25 s, and exposure to a train of pulses.

Table 2.1 Comparison of MPE for Visible Laser Radiation

Standard	Single Pulse 0.01 s	Accidental Exposure (0.25 s) to cw Beam	Exposure to Pulse Train for 1000 s, 100 Hz and 1 ms pulses (MPE/pulse)
Ministry of Aviation 1964	2 mJ m^{-2}	5 mJ m^{-2}	0.2 mJ m^{-2}
Ministry of Technology 1969	1 mJ m^{-2}	0.3 J m^{-2}	0.003 mJ m^{-2}
BS 4803: 1972	1 mJ m^{-2}	0.3 J m^{-2}	0.003 mJ m^{-2}
BS 4803: 1983	0.57 J m^{-2}	6.36 J m^{-2}	1 mJ m^{-2}
BS 7192: 1989	0.57 J m^{-2}	6.36 J m^{-2}	1 mJ m^{-2}
BS EN 60825: 1992	0.57 J m^{-2}	6.36 J m^{-2}	1 mJ m^{-2}
BS EN 60825-1: 1994	0.57 J m^{-2}	6.36 J m^{-2}	1 mJ m^{-2}

It can be seen that the MPE level has remained unchanged since the publication of BS 4803: 1983. Guidance document PM19 contains a table which agrees with the 1983 and later values in table 2.1 for the single pulse and cw exposure situation. However, the scanned condition is not specifically addressed. The only change to the MPE values since the laser was first used in laser light shows appears to be the relaxation in all three values in table 2.1 between 1972 and 1983.

The current British Standard (BSI 1994) contains three sections. Sections 1 and 2, definitions and manufacturer's requirements, respectively, are normative and should be complied with. Section 3 is the user's guide and there is a reference to the use of lasers for entertainment (sub-clause 12.4):

> Only Class 1 or Class 2 laser products may be used for demonstration, display or

> entertainment in unsupervised areas. The use of lasers of a higher class for such purposes should be permitted only when the laser operation is under the control of an experienced, well-trained operator and/or when spectators are prevented from exposure to levels exceeding the applicable MPE.

The British Standard recognises that laser radiation is not the only hazard which needs to be addressed. Clause 11 considers these 'hazards incidental to laser operation'. The rationale behind the inclusion of other hazards for lasers is based on incidents over the last thirty five years.

Many lasers operate at high voltages, or at least have an input from the mains supply (230 V in Europe). The laser assemblies are also heavy, presenting a risk of mechanical damage to installers and others in the vicinity. The types of lasers used in the entertainment industry do not generally use chemicals such as fluorescent dyes. However, in industry such materials are widely used and need to be subject to special care. The review of laser-related incidents by Rockwell (1997), reports non-radiation laser incidents as follows: 24 fires; 12 electric shock incidents (5 of which were fatal) and 4 embolisms (gas injection into blood stream), three of which were fatal. There were also 11 other incidents of a similar nature which were as a result of, for example, equipment failure. There is no specific data on incidents involving lasers in the entertainment industry.

This analysis demonstrates that non-laser radiation hazards have killed people. Certainly high voltages will be present around many entertainment lasers. High power lasers will also have the potential to cause fires and there is some anecdotal evidence that they have done so in entertainment venues.

2.4.2 International Standards

Most British Standards involving lasers are initiated and developed through the work of the International Electrotechnical Commission technical committee 76. The current British Standard on laser safety is technically equivalent to IEC 60825-1: 1993 (IEC 1993). It was recognised by the members of technical committee 76 that the base standard did not give adequate guidance for the use of display lasers. This was developed in a Technical Report, IEC 60825-3: 1995 Guidance for Laser Displays and Shows (IEC 1995). The status of this document is that it is a code of practice and not a standard.

IEC 60825-3 builds on the Australian code of practice reviewed in section 2.2.3. Ancillary personnel and performer MPEs are introduced to recognise that these persons may be trained in laser safety issues, something that cannot be assumed for the audience.

The International Radiation Protection Association (IRPA) Non-Ionizing Radiation Committee published guidelines on protection against non-ionising radiations in the journal Health Physics. These have been compiled into a comprehensive manual (IRPA, 1991). This includes a chapter on guidelines on limits of exposure to laser radiation of wavelengths between 180 nm and 1 mm. In May 1992 IRPA established an independent scientific organisation - the International Commission on Non-Ionizing Radiation Protection (ICNIRP). This body revised its laser radiation guidelines in 1996 (ICNIRP, 1996). The exposure limits are identical to the maximum permissible exposure limits in the IEC standards.

The American Conference of Governmental Industrial Hygienists (ACGIH) publish threshold limit values (TLVs) for physical agents, including lasers. The TLVs from the 1992-1993 edition are incorporated into a proposed European Directive on Physical Agents (CEU, 1994). Again, the expressions used for the TLVs are identical to the maximum permissible exposure values in the IEC standards for the visible part of the electromagnetic spectrum.

2.4.3 Summary of Standards

Laser safety standards have primarily been developed for the manufacture of equipment such that persons are protected from exposure to laser radiation. The inclusion of other hazards has been recent. The maximum permissible exposure levels have remained constant within the visible part of the electromagnetic spectrum since about 1983. The same standard is applied throughout the world, produced by the International

Electrotechnical Commission. The scientific basis for the maximum permissible exposure levels continues to be studied by the International Commission on Non-Ionizing Radiation Protection. It is significant that the maximum levels of exposure for the visible region of the electromagnetic spectrum is identical in all of the standards, although the terminology may be different.

None of the standards use risk assessment, except within IEC 60825-1 for the use of class 1. Sub-clause 9.2 uses the concept of "reasonably foreseeable conditions of operation" in the definition of a class 1 laser product.

2.5 Legislation

The regulation of the use of lasers in the entertainment industry is complex. Many of the concerns from the laser display industry were from the confusion as a result of this complexity. Health and safety legislation applies to all work activities, irrespective of where that work is carried out. There is no specific health and safety legislation covering the use of lasers. However, much of the work will be subject to non-laser-specific health and safety legislation covering general health and safety, specific hazards and specific work activities. Some laser display events will require an entertainment licence. Some laser-related equipment will be subject to legislation concerning its supply.

2.5.1 Enforcement of Health and Safety Legislation

The principal health and safety legislation in the UK is the Health and Safety at Work etc Act 1974 (HMSO 1974). This legislation was the result of a report from a Committee chaired by Lord Robens (Robens 1972) into the status of health and safety legislation in the UK. Significantly, the Committee was asked to consider whether changes to legislation were needed to protect members of the public from hazards "arising in connection with activities in industrial and commercial premises". The report from the Committee describes a number of incidents where members of the public have been killed or injured as the result of the work activities of others. Most legislation at the time only dealt with the health and safety of employees and the recommendations from various official tribunals and investigations had not been addressed. Section 1 of the Health and Safety at Work etc Act states that one of the aims of the Act is to protect people who are not employees but who may be at risk due to the activities of people at work. This provision clearly applies to the public attending an entertainment event where lasers are used and the laser display company's staff, and others, are at work.

The enforcement of health and safety legislation in the UK is either by the Health and Safety Executive or by the local authority. The division of responsibility is laid down in the Health and Safety (Enforcing Authority) Regulations 1998 (HMSO 1998), which replace earlier Regulations (HMSO 1989).

A summary of the relevant premises where the Health and Safety Executive (HSE) and local authority (LA) will be the enforcing authority are presented in table 2.2.

Table 2.2 Enforcement of Health and Safety Legislation

Premises	Enforcing Authority
Laser Company's Premises	Generally HSE
University Campus	HSE
Arts, Sports, Games, Entertainment or Other Cultural or Recreational Activity	LA
As above, but LA is Owner or Operator	HSE
Fairground	HSE
Radio, Television or Film Undertaking	HSE
Sea-Going Ship	HSE
Zoo or Wildlife Park	LA

It can be seen that HSE are the enforcing authority for a greater range of types of establishments where lasers may be used for entertainment. However, the number of premises falling within the "Arts, Sports, Games, Entertainment or Other Cultural or Recreational Activity" category are large. Enforcement within the local authority is generally carried out by Environmental Health Officers (EHOs), whose duties may also extend to enforcement of the Public Health Acts.

The Health and Safety Executive is a national body. The enforcement is carried out through regional inspectors who can call on specialist inspectors when necessary. At the time of writing, the HSE had four specialist inspectors with responsibility for radiation, including lasers. These, in turn, are supported by a member of staff from the Directorate of Science and Technology who develops HSE guidance in this area and represents the organisation at national and international level.

Local authorities operate autonomously throughout the UK and, in England, may by a county council, if there are no district councils within the county, district councils, London borough councils, the Common Council of the City of London, the Sub-Treasurer of the Inner Temple, the Under-Treasurer of the Middle Temple or the Council of the Isles of Scilly. In Scotland the local authority is a council for a local government area and in Wales a county council or a county borough council. Therefore, there are many local authorities, all of which may have a number of staff who enforce health and safety legislation.

2.5.2 Health and Safety Legislation

The Health and Safety at Work etc Act is an enabling Act. There are a number of Regulations, made under the Act, which are, or could be, relevant to the use of lasers for entertainment. These are summarised in table 2.3.

Risk assessment is introduced in the Health and Safety at Work etc Act. The concept of "so far as is reasonably practicable" to ensure work activities are "safe and without risks to health" is used throughout. The duty applies firstly to the employer, but also to the designer, manufacturer, supplier and installer as well as generally to the employee. All of these are important for the laser entertainment industry, but perhaps the most important is the last. The employees setting up and operating a laser display will need to ensure that the laser display is safe and without risks to health. The Act gives no guidance on how safety should be demonstrated and risks assessed.

Table 2.3 Safety Legislation Relevant to the Use of Lasers in the Entertainment Industry

Title	Abbreviation
Health and Safety at Work etc Act 1974	HSAWA
The Reporting of Injuries, Diseases and Dangerous Occurrences Regulations 1995	RIDDOR
Ionising Radiations Regulations 1985	IRR
Electricity at Work Regulations 1989	EAWR
Management of Health and Safety at Work Regulations 1992	MHSWR
Provision and Use of Work Equipment Regulations 1992	PUWER
Manual Handling Operations Regulations 1992	MHOR
Workplace (Health, Safety and Welfare) Regulations 1992	WHSWR
Personal Protective Equipment at Work Regulations 1992	PPEAWR
Health and Safety (Display Screen Equipment) Regulations 1992	HSDSER
Control of Substances Hazardous to Health Regulations 1994	COSHH
The Health and Safety (Safety Signs and Signals) Regulations 1996	SSR

The Management of Health and Safety at Work Regulations 1992 (HMSO 1992) requires a "suitable and sufficient" assessment of the risks from a work activity to be carried out (Regulation 3). Again, little practical guidance is provided in the Regulations on how to achieve this. General practical guidance has followed the introduction of the legislation after recognition by the HSE and others that many small and medium size businesses did not understand what was required for a suitable and sufficient assessment of risks. Indeed, many businesses appeared to consider that such assessments did not apply to them, and were only an issue for the chemical or nuclear industries. The "Five Steps to Risk

Assessment" was a simple approach to risk assessment which is applicable to many work activities (HSE 1998). HSE also recognised that the issue was risk management and not only risk assessment (HSE 1995).

There is no specific health and safety legislation relating to the use of lasers. The general legislation described above applies in many cases. Where national or international standards, or industry-specific guidance exists, these may be used as a measure of good practice for the practical application and enforcement of the general health and safety legislation.

2.5.3 Entertainment Licensing Legislation

Certain entertainment activities are licensed by local authorities. The officers may be from the Environmental Health department and therefore also involved with the enforcement of health and safety legislation or they may be in separate departments. Different legislation applies in different parts of the UK and in certain types of venue. The different legislation is summarised in table 2.4.

"Reasonableness" is used in licensing legislation as opposed to "as far as is reasonably practicable" in health and safety legislation. Reasonably practicable is taken to mean that the time, trouble, cost and physical difficulty of taking steps to avoid the risk are not wholly disproportionate to the risk. The size or financial position of the employer is not taken into account in this calculation. However, reasonableness may go further and local authorities may impose requirements under the entertainment licence which will achieve higher standards than those required under health and safety legislation (HMSO 1993).

Table 2.4 Entertainment Licensing Legislation

Legislation	Comments
Local Government (Miscellaneous Provisions) Act 1982	Applies to England and Wales (except London). For open air events, safety is a specific consideration. Uses the concept of reasonableness. Licence conditions can be specified. Covers public dancing or music or "any other public entertainment of a like kind".
London Government Act 1963	Applies to London. No distinction between indoor and open air events.
Civic Government (Scotland) Act 1982	Applies to Scotland. Covers locations where payment of money or money's worth is made for entertainment or recreation.
Private Places of Entertainment (Licensing) Act 1967	Applies to private premises operated for private gain and public not admitted.
Theatres Act 1968	Covers theatres where dancing or music do not form a significant part of the entertainment.

2.5.4 Product Supply Legislation

Article 18 of the Single European Act (EU 1987) introduced Article 100 A to the Treaty establishing the European Economic Community. Article 100 A established the internal market, ie provided for the free movement of goods between member states which should provide a basic level of health and safety to consumers. The Electrical Equipment (Safety) Regulations 1994 (HMSO 1994) covers equipment operating between 50 V and 1000 V AC, which includes most electrical equipment involved in laser displays. The Regulations refer to harmonised standards which should be used as the guide to the essential health and safety requirements such equipment should be expected to meet. In terms of laser equipment this will be the current British Standard on laser safety (BSI 1994).

Although the Electrical Equipment (Safety) Regulations were made under consumer law (Consumer Protection Act 1987) and are generally enforced by Trading Standards Authorities (Department of Trade and Industry), the Regulations are also relevant to workplace legislation such as the Health and Safety at Work etc Act 1974 and the Provision and Use or Work Equipment Regulations 1992, where the Health and Safety Executive or Local Authority Environmental Health Officers will be the enforcing authorities.

2.5.5 Summary of Legislation

It can be seen that the legislation concerning the use of lasers in entertainment is complex. The complexity is compounded by the lack of specific legislation for the use of lasers. The enforcement of the general legislation may be by different agencies and different groups of people within those agencies.

In summary, health and safety legislation will always apply. The enforcement will either be by the Health and Safety Executive or the local authority. Entertainment legislation may apply. If dancing or music forms part of the entertainment then it probably does apply. This is enforced by the local authority. Mains-powered equipment supplied as part of the laser display may be subject to product legislation. Enforcement of the supply will be by the Department of Trade and Industry, but there may also be implication under health and safety legislation.

The role of the police and fire services also need consideration. The use of lasers may cause a disturbance if used in the open air. The fire service may be involved due to the use of high voltages, water and the risk of fire from laser radiation.

Open air use of lasers may have an effect on air safety. The Air Navigation (No. 2) Order 1995 (HMSO 1995) can be used to control the use of lasers. Persons can be prosecuted for endangering the safety of aircraft (Article 55) or for exhibiting lights which may endanger aircraft taking off or landing, or which may be mistaken for landing lights (Article 99). The author assisted with drafting guidance for the use of lasers in airspace

(CAA 1998). Airspace safety is enforced in the UK by the Civil Aviation Authority.

2.6 General Risk Assessment

It is obvious from the literature that no specific guidance is available for undertaking risk assessment for the use of lasers in the entertainment industry. There is limited guidance on risk assessment for the entertainment industry as a whole. However, other sectors such as the chemical and nuclear industries have been undertaking risk assessments for a number of years.

The Health & Safety Executive (HSE) published a report which looked into the tolerability of risk from nuclear power stations (HSE, 1988). This introduced the concept of 'individual risk' as compared with the 'societal risk'. The individual's perception of risk is very dependent on their perception of whether there is a positive benefit to them and whether their exposure to the risk is voluntary. The HSE use this concept further in a document on quantified risk assessment (HSE, 1989).

Death has been the usual outcome that has been associated with risk. However, the quality of life is now recognised as being important. One of the simplest ways of quantifying a risk is to take the number of incidents of a particular outcome per unit time or number of times the activity took place. However, consideration also has to be given to circumstances where the link between the cause and effect is not certain and some assumptions have to be made, and where no incidents have occurred, either because the probability of the outcome is very small or because the activity has not yet commenced. In this case 'best estimates' are used (Royal Society, 1992).

Taking the specific case of a family attending an entertainment event which includes the use of lasers, the perception will be that the risk to them is zero. The tolerability of risk will also be low. For a specific event it will not be acceptable to expose the public to a known hazard without quantifying the hazard and minimising the risk, taking account both the probability of exposure to the hazard and the consequences of exposure. In this sense best estimates could be used provided the hazards have been identified and quantified. It would be reasonable to expect control measures to be implemented if the risk was too high.

This approach is used, for example, when considering crowd management at entertainment events. Some of the incidents have resulted in many deaths, for example in Jerusalem in 1834 500 people died; 190 children died in a stampede against a restricted doorway in a theatre in Sunderland in 1883; and 99 football supporters died when they were crushed against a barrier in Hillsborough in 1989 (Kletz 1993). The significance of these incidents is twofold - first the number of people involved; and second the apparent inordinate amount of time before anything is done about the risk of repeat incidents. The Pop Guide (HMSO 1993) provides formulae for calculating the maximum number of people inside an event to minimise the risk of crowd-related problems. The HSE have also produced a guide on managing crowd safety (HSE 1996b) which is a practical guide to the safety issues which need to be considered. The parallels with laser safety in the entertainment industry are clear. A large number of people have been exposed to the hazard for a number of years and the potential for causing injury to a large number of people exists.

The military have been interested in the use of probabilistic risk assessment for laser safety for some years (Smerden 1986, Gardner and Smith 1995). The use of laser range finders on aircraft during training flights can potentially give rise to public exposure. The nominal ocular hazard area can extend over many square kilometres if taken literally from standards. The argument suggested is that although the MPE may be exceeded, the actual probability of exposure is very small. To support this, the concept of the minimum ophthalmoscopically visible lesion (MOVL) is used, which is assumed to be a 30 μm retinal lesion. An acceptable risk level of 10^{-8} is used. Whilst this approach may be acceptable for military applications, it is less likely to be acceptable for routine public exposure in entertainment. An important factor is again the perception by the average family that the activity, ie going to a laser display, should be safe and without risk.

A formal approach to risk assessment is to consider the components of the laser display equipment and consider what can go wrong. There are a number of standard texts on methods for carrying out the analysis, for example (Cox and Tait 1991; Modarres 1993; Henley and Kumamoto 1992; and Kletz 1992). However, as pointed out by Kletz (1991) one of the major factors is the human being, either as the manager, or as the person carrying out a physical activity. A report from the Advisory Committee on the Safety of Nuclear Installations (ACSNI 1993) supports this view and suggests that a positive safety culture is very important. An analysis of the individual components of each laser display may not be viable considering the time constraints, certainly on temporary installations. However, for permanent installations, if the risk of exposure is high and the number of people at risk is large, then it may be appropriate to utilise the more formal techniques such as hazard and operability studies, hazard analysis and failure modes and effects analysis. However, as stated above, the nature of the industry is such that assumptions may still need to be made about the human factors in the assessment.

2.7 Training

Section 2.6 has identified the importance of the human element in the assessment of the risks. Training can form an important part of risk management. The current laser safety standard (IEC 1993) provides some guidance on the training required for users of class 3A or higher laser products. The standard suggests that this training should include:

- familiarisation with system operating procedures
- the proper use of hazard control procedures, warning signs, etc
- the need for personal protection
- accident reporting procedures
- bioeffects of the laser upon the eye and the skin

The standard also requires a Laser Safety Officer to be appointed if a laser of class 3B or class 4 is used.

Vassie et al (1993) reported that many of the laser manufacturers in the UK had difficulty understanding the current British Standard on laser safety. Many purchasers of laser products will rely on the manufacturer for education and training in the first instance. It would be reasonable to expect laser display companies of some standing to have laser safety training programmes which include all of the hazards from working in the industry.

It would also be reasonable to see customer training provided, perhaps under the guidance of the company Laser Safety Officer.

Trade associations often have an important role in the maintenance of practical standards for particular industries. However, the development of such associations, particularly in the UK has to be seen in the context of the competition between laser display companies. Many companies have spawned other companies through personal differences between employers and employees.

The International Laser Display Association (ILDA) is a US-based organisation founded in August 1986. It publishes its own journal (Laserist) and holds an annual conference. There are currently seven committees: Awards; Technical; Safety; Ethics; Terminology Standardization; Planetaria and Science Centers; and Public Awareness. ILDA publish (ILDA 1993) a glossary of terms used in the laser entertainment industry aimed primarily at new laser operators and technical standards.

A Canadian laser display company, Laser F/X International, publishes its own journal for the laser light show industry (Laser Effects). This has a worldwide circulation. Laser F/X International also organises an annual laser light show conference and exhibition which includes tutorial sessions.

Both ILDA and Laser F/X International operate sites on the Internet, with electronic mailing lists for the exchange of information.

There is no major involvement of UK laser display companies in these two ventures.

Following a joint presentation of new guidance by the Health and Safety Executive (HSE 1996a) by NRPB, Loughborough University and the Health and Safety Executive on 8 January 1997, many of the laser display companies got together and formed a professional association. Initially this was called the British Entertainment Laser Association, but the "British" was deleted within a couple of months to avoid limiting the membership to the UK. The birth of this organisation could be seen to be as the result of implied tighter regulation of the industry and therefore was initially a pressure group.

2.8 Conclusions

There are a number of guidance documents covering the use of lasers in the entertainment industry. None of these give practical guidance on assessing the risks. Most of the documents are official, ie have been written by regulators rather by the industry. The guidance that has been written by the industry contains errors and demonstrates a lack of understanding of many of the safety issues.

The guidance for the exposure of persons, and particularly members of the public, to laser radiation is consistent and clear. People should not be exposed to laser radiation in excess of the maximum permissible exposure (MPE). The values for the MPEs are internationally agreed and have remained the same for the visible region of the electromagnetic spectrum since at least 1983. However, there is no clear guidance on how to assess laser shows for compliance with the MPE values.

The enforcement of the use of lasers in the entertainment industry is complex and needs to take account of health and safety legislation, entertainment licensing and product legislation. The enforcement is likely to be spread over different agencies, and many enforcing officers are unlikely to deal with the entertainment use of lasers regularly, even in major population centres.

Laser radiation is unlikely to kill people. Many of the associated hazards, such as electricity, working at height and manual handling do have a risk of death. There is specific legislation covering many of these hazards and general entertainment industry guidance. However, laser displays are usually seen in isolation, as is clear from the guidance documents available.

Industries who work together in professional associations tend to develop their own standards, both technical and safety. The laser display industry in the UK is highly competitive with a high degree of animosity between companies, many of which share evolutionary paths. This is likely to lead to a reluctance to be open about the technology used for laser display products.

The conclusion is that the industry is likely to be very protective of its activities, especially as there appears to have been little formal involvement of regulatory authorities in assessing the risks from actual performances. The prevailing view of the laser companies is that they have been carrying out this activity for a number of years and that they know what they are doing. The view of the regulators is likely to be that the industry is not helpful and probably not able to demonstrate the risk management of their activities. Such views are likely to see each party on either side of a ravine with a large gap of understanding between them, but each, hopefully, will have the common aim of seeing the safe use of lasers in the entertainment industry. It was clear, therefore, that it was necessary to understand the technology and issues associated with putting on a laser display, the practical approach to assessing the risks, and the problems of enforcement. In essence, the laser display companies had to be able to provide risk assessments which were meaningful, and which could be assessed by enforcing officers to ensure legal compliance. If this could be achieved, it should be possible to build a bridge between the two opposing sides and ensure the safety of all who attend entertainment events using lasers.

3. Background for the Research

3.1 Introduction

There are a number of applications for lasers in the entertainment and display industry. The examples described here represent a cross section of these applications and are events where the author was involved either as the laser safety adviser to the enforcing authority or attended at the request of the organisers or venue operator. The involvement was at the start of the research.

There is currently no published comprehensive review of the laser systems used by the entertainment industry in the UK. This puts the enforcing officer at a disadvantage in that s/he may not be familiar with the technology and have no reference to turn to. At the start of this research the laser companies were reluctant to reveal details of the hardware used. This was justified by them on the basis of fierce competition within the UK. This approach appears to be different from that in the United States and Canada where standardisation has been encouraged and shows are transferred between companies on magnetic tape. Laser F/X International have recently published a guide to the equipment used in North America (Roberts, 1996), but this does not cover the safety aspects of individual components in any detail.

3.1.1 Details of Laser Display Systems

An outline block diagram of a simple laser display system is presented in figure 3.1.

In order to use laser radiation for entertainment, it is necessary to have laser beams that are visible. This means that the radiation should be within the wavelength range 400 to 780 nm, and a proportion of the beam needs to enter the eye to stimulate the optical sensors on the retina. The eye does not respond equally to all wavelengths. Therefore, in order to achieve the same level of "brightness", different irradiance levels on the retina are required. The absolute luminosity curve for the eye's photopic (high light level) response is presented in figure 3.2 on a linear/log scale to emphasise the contribution at the visible wavelength extremes (after Anderson 1989). Combining visible radiation of different wavelengths produces white light. Since the mixture relies on the visual perception of the light, it is important that the irradiances on the retina are matched to the inverse of the curve in figure 3.2. The use of multiple colours is more important for graphical images than for beam effects. These are discussed in more detail below.

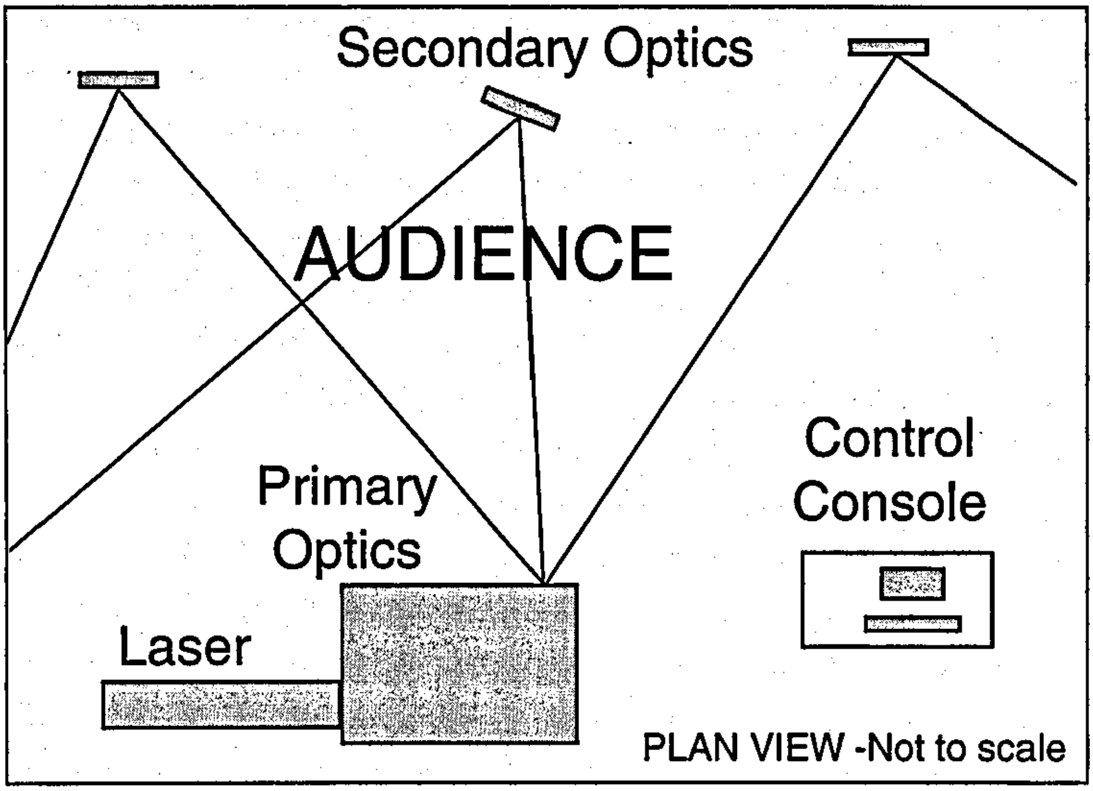


Figure 3.1 Simple Laser Display System

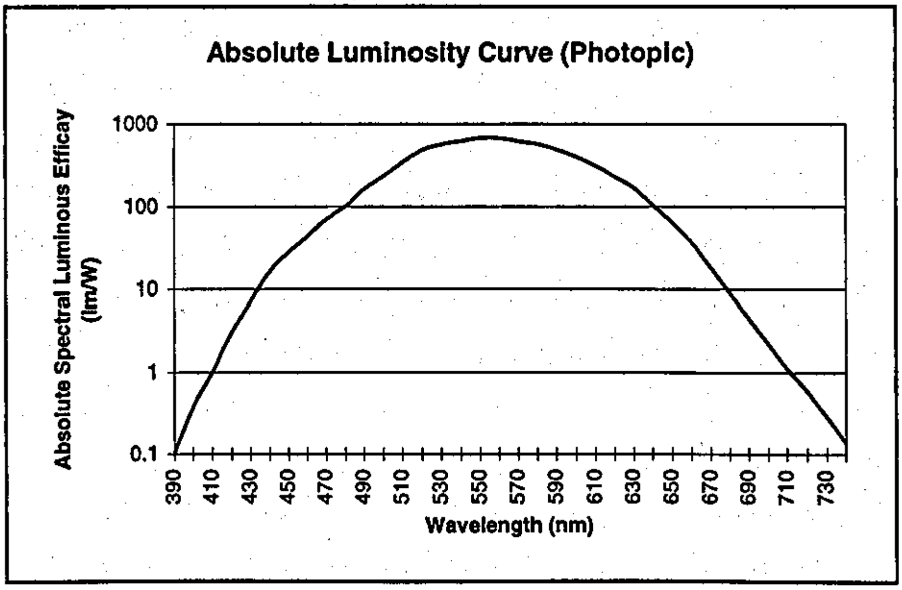


Figure 3.2 Absolute Luminosity Curve (Photopic)

A number of different types of laser are used in the entertainment industry. The types described here are restricted to those which emit laser radiation in the visible part of the electromagnetic spectrum. It is unlikely that lasers emitting infrared radiation will be employed but it is accepted that there may be some experimentation with lasers emitting ultraviolet radiation (UVR). UVR can be used to induce fluorescence in certain materials, including cosmetics. However, the collimated nature of laser radiation is a disadvantage for such applications.

There is limited information about the number of lasers used in the entertainment industry but there is an indication of the number of units sold per year from the annual review and forecast covering all laser applications published by Laser Focus World. The information relating to entertainment also covers laser pointers, laser-based information displays, display holograms and laser projection systems. The data from the 1995, 1996, 1997 and 1998 review and forecasts are presented in table 3.1 for world-wide sales (Anderson 1995, 1996, 1997 and 1998). All other categories were zero. It was recognised that China and Asia represent growing entertainment markets.

Diode lasers, including laser pointers, have not been included in this table. The data was collected by contacting manufacturers throughout the world. However, it is known that a number of laser display companies are using metal vapour lasers whereas the data in table 3.1 suggests that these have moved out of favour. The sudden growth of diode-pumped solid state lasers is ably demonstrated.

Table 3.1 only considers lasers sold new into the entertainment industry and also probably ignores small manufacturing bases. A number of the lasers used in the entertainment industry move into the sector as second hand products from other industries. There are also a small number of dedicated manufacturing bases. However, the latter probably represent less than ten units per year in the UK, although most of these are solid state lasers.

Table 3.1 Laser Focus World Review and Forecast of Worldwide Laser Sales (Units)

	1994 (Actual)	1995 (Actual)	1996 (Actual)	1997 (Actual)	1998 (Forecast)
Solid State - Lamp Pumped	40	50	15	20	25
Solid State - Diode Pumped	0	0	20	50	90
Ion < 1W	316	207	154	200	200
Ion > 1W	257	289	305	286	299
He-Cd	20	25	0	0	0
He-Ne	5500	7000	7750	5000	5000
Metal Vapour	5	0	0	0	0
Total	6138	7571	8244	5556	5614

This section reviews some of the laser display systems used and is based on discussions with a number of laser companies. Although there was a belief that they all had unique systems, they were all very similar in concept, if not in detail. The safety issues associated with the various components of the laser display are presented. Further details of the equipment used are contained in Appendix 1.

3.1.1.1 Lasers

Table 3.1 shows the types of lasers sold for use in the entertainment industry. Each have safety issues associated with them (see table 3.3). The wavelengths used for entertainment applications from each type of laser are summarised in table 3.2.

Table 3.2 - Principal Wavelengths from Lasers Used in Entertainment

Type of Laser	Principal Entertainment Wavelengths (nm)
Solid State - Lamp or Diode Pumped	
Nd:YAG (frequency doubled)	532
Ion	
Argon-ion	457.9, 476.5, 488.0, 514.5
Krypton-ion	406.7, 413.1, 468.0, 530.9, 568.2, 647.1, 676.4
Mixed Gas or “white light”	457.9, 476.5, 488.0, 514.5, 530.9, 568.2, 647.1, 676.4
He-Cd	441.6, 537.8, 636.0
He-Ne	543.5, 594.1, 604.0, 611.9, 632.8, 640.1
Metal Vapour	
Copper Vapour	510.6, 578.2
Gold Vapour	628.0
Dye Lasers	Various
Semiconductor Lasers	Various

As has already been discussed in 3.1.1, the eye's response, in terms of how bright a light source is for a fixed irradiance, depends on the wavelength. White light can be generated by mixing the wavelengths either from a single laser or two or more lasers. However, in order to achieve true white light (as perceived by the eye) it is necessary to mix the irradiances at each wavelength in inverse proportion to the photopic response of the eye. There are essentially two types of visible effect that are produced: beams in the air and graphical images. Usually, the effects are mutually exclusive, ie with graphical images it is preferable not to have the beams visible in the air; and with beam effects it is generally undesirable to see the eventual target site of the beams.

The safety issues associated with each of the types of laser in table 3.2 are summarised in table 3.3. Some of the hazards will only be accessible during maintenance or servicing of the laser. However, since these operations are routinely carried out by staff from the laser companies it is important that they are included here.

Table 3.3 - Hazards Associated with Entertainment Lasers (in Addition to Visible Laser Radiation)

Type of Laser	Invisible Laser Radiation	Incoherent Optical Radiation	High Voltages	Weight	Moving Parts	Coolant	X-Rays	Temperature	Implosion	Chemicals
Solid State - Lamp pumped	✓	✓	✓	✓	✓	✓		✓	✓	
Solid State - Diode Pumped	✓			✓	✓	✓		✓		
Ion			✓	✓	✓	✓		✓	✓	
He-Cd	✓		✓	✓	✓	✓		✓	✓	
He-Ne			✓					✓	✓	
Metal Vapour			✓	✓	✓	✓	✓	✓		
Dye	✓(?)	✓(?)	✓	✓	✓	✓		✓	✓	✓
Semiconductor	✓(?)			✓(?)						

Key: ✓ this hazard generally exists for this type of laser.

✓(?) depends on the specific type of laser. The hazards associated with dye lasers may be due to the pumping laser.

The typical mode of operation and current maximum radiant powers for typical entertainment lasers are summarised in table 3.4.

Table 3.4 Summary of Common Entertainment Lasers

Laser	Mode of Operation	Radiant Power Range (in Entertainment)
Helium-Neon	Continuous	< 1 mW to 75 mW
Argon-ion	Continuous	50 mW to 50 W
Krypton-ion	Continuous	50 mW to 5 W
Mixed Gas	Continuous	50 mW to 5 W
Helium-Cadmium	Continuous	up to 150 mW
Copper Vapour	Pulsed	up to 100 W average
Gold Vapour	Pulsed	up to 5 W average
Neodymium:YAG (frequency doubled)	Continuous or Q-switched	up to 50 W average
Semiconductor	Continuous	up to 5 W (array)

It is possible that other lasers could be used for entertainment applications but the list considered in this section represents the majority of the types of lasers in use today. The continuous development of the semiconductor laser will mean that three-colour semiconductor products will eventually come on to the market.

As described in the previous chapter, laser radiation safety appears to be well addressed, with information to assess the magnitude of the hazard given in the current British Standard (BSI, 1994). In order to make the assessment for a given laser, the following information will be required:

- wavelength;
- radiant power or energy;
- pulse characteristics;
- beam divergence; and
- initial beam diameter.

There may be some inconsistencies in the way some of this data is presented by manufacturers. The beam is generally assumed to have a Gaussian profile. The beam diameter may be quoted at the 1/e or $1/e^2$ points. The divergence may be quoted as a full or half angle. It is also possible that some lasers will have a beam waist outside the laser aperture.

3.1.1.2 Associated Equipment

A semiconductor laser may be a complete unit, including all power sources. Most of the other lasers will at least have an electrical power cable which needs to be connected to an electricity supply. Lasers, such as the argon-ion laser, may consist of a laser head, an "exciter" unit, which provides the necessary high voltages, a control module, cooling water supply and all of the associated cables and pipework to connect the various parts together.

A summary of the equipment associated with running an entertainment laser is presented in table 3.5, along with the resultant hazards.

Table 3.5 Hazards from Associated Equipment

Equipment, etc	Hazards
Generator	Noise, High Voltages (may be three-phase supply), Fuel, Heat, Fumes, Weight
Laser Exciter	High Voltages, Weight
Control Module	Uncontrolled Access
Cooling Plant	Noise, Water/Coolant, Pressure, Heat, Weight
Water Storage Tanks	Weight, Water (potential risk of drowning)
Support Stand	Weight, Stability
Electrical Cables/Control Cables	High Voltages, Trip Hazards
Cooling Pipes	Trip Hazards, Pressure, Water/Coolant

3.1.1.3 Optical Systems

The laser may be used without any other optical components to produce a display. However, it is more likely that the beam will be directed through optical systems to produce various visual effects.

There are three optical systems which need to be considered:

- the transfer of the beam from the laser to one or a number of primary optical processing systems;
- primary optical processing, normally within an optical bench; and
- secondary optics, normally mounted around the venue and including the final target site(s) for the laser beam(s).

Any one of the optical systems can alter the characteristics of the laser beam, including the temporal characteristics, the radiant power or energy, beam diameter and beam divergence.

The transfer of the beam from the laser to the primary optical system may be through the open air, through a beam tube or through a fibre optic cable. The laser may be mounted within an enclosure with the primary optical system, it may be coupled directly to the enclosure, or may be remote.

The optical systems may contain a number of components which may also alter the characteristics of the beam. Typical components are summarised in table 3.6. Further descriptions of the individual components are given in Appendix 1.

Table 3.6 Summary of Components in Optical Systems

Component	Characteristics
Beam Dump	May be a specific absorber block, local shielding within the primary optical system or part of the venue structure. Essentially, the place where the beam is terminated. May be the place where reflected beams from, for example, dichroic filters are dumped. Should be sufficient to cope with the maximum irradiance likely to be encountered at that position.
Beam Scanners	Deflect beam under control. May be mirror mounted on motor shaft, galvanometer pairs or acousto-optic modulators. Used to generate aerial beam effects and images on screens. Can be considered a moving form of the plane mirror.
Beam Splitters	An incoming beam is split into two beams. The split may be 50-50, or any other ratio. Can be used to generate more than one effect simultaneously from a single laser beam.
Beam Stop	Generally, a mechanical shutter placed in the beam path. May be activated by a solenoid. May be switched out of the beam path at the start of a show and back in at the end of the show.
Colour Selectors	May be dichroic mirrors or a polychromatic acousto-optic modulator. The dichroic mirrors may be mounted on rotary actuators. Consideration has to be given to the unwanted portion of the beam.
Diffraction Grating	May be transmission or reflection. May have zero order suppressed. Beam power effectively split over a greater area.
Effects Wheel	May contain a number of optical components such as diffraction gratings, and also a straight through position. The wheel rotates under control to select the different positions.
Lenses	May be used to focus or diverge the laser beam. May be used as part of the Z-Blanking system or to increase the beam divergence at the exit aperture of the primary optical system. The use of a lens anywhere in the beam path will suggest that the beam divergence provided by the manufacturer of the laser will not be valid for the beam after the lens. The use of a convex lens may produce a focal point external to the aperture from the primary optical system
Luminaires	Glass or plastic which influences the path of the beam. Shower glass or other optically transmitting material which has a surface texture is generally used. A prism or a polychromatic acousto-optic modulator may be used to split the colours before passing through the luminaire.
Masking Plates	Physical blanking plates which may be located at the exit apertures of the primary optical system to restrict the possible beam paths to avoid exposure, for example, of the audience. May also be incorporated into secondary optical components to reduce the effect of unplanned component movement.
Mirror Balls	A secondary optical component which has multiple facets of either plane or diffraction mirrors. The facets may be of similar dimensions to the laser beam, in which case the beam is scanned across the mirror ball, or the beam may be diverged through a lens to fill the mirror ball.

Table 3.6 Summary of Components in Optical Systems (continued)

Component	Characteristics
Plane Mirrors	Front or rear silvered mirrors. Assume total reflection with all beam characteristics except direction conserved.
Projection Screens	May be a standard projection screen or may be any other surface, including buildings, trees and clouds, on which the laser beam is projected. The projection screen may have reflecting surfaces or may transmit a proportion of the incident beam.
Rotary Actuators	Usually has something mounted on an arm which is introduced into the beam under control. Can be used to switch beam paths, block beam paths and remove specific wavelengths from the laser beam.
Z-Blanking	Generally either a galvanometer or an acousto-optic modulator which switches the beam on and off under control. Used so that the beam position can be moved without being seen.

3.1.1.4 Control Systems

The laser display is usually controlled by one of three methods: manually, programmable controller, computer-based controller. The controller generally does not control the laser itself: this was considered in 3.1.1.2. However, it will control all of the primary optical system and possibly secondary optics. It may control associated equipment such as smoke generators, electric screens, water screens, etc. Programmable controls are considered here to include systems which incorporate a tape player to present pre-recorded laser shows. The controller will be linked to the equipment it is intended to control. This may be by wire, fibre optic cable link or by radio/infrared free-in-air link. Each of these will have safety issues associated with them. The trend towards computer control and digital communications may provide the opportunity for increased fault tolerance but also provides the opportunity for communication over greater distances via network systems. This may result in global control of many laser displays in different countries at the same time from a central point. This approach is already used for permanent small-scale laser displays in shopping malls. These are generally used to display textual images and logos and are programmed from a central location (Lissack, 1995).

A summary of the safety issues associated with the control systems is presented in table 3.7.

Table 3.7 Safety Issues from Control Systems

Item	Safety Issues
Manual Controller	Degree of operator control. Potential for pressing wrong button. Ability to alter show from what has been agreed.
Programmable Controller	Programming errors.
Computer-based Controller	Computer failures. Interference from other equipment. Programming errors.
Communication Channels	Loss of communication. Interference with communication.
Operator	Training. Degree of control. Pressure of work (stress).
Power Supplies	Failure. Malfunction. What happens to optical systems under these circumstances? High voltages.

3.2 Lasers in Entertainment

A number of applications of lasers in entertainment were reviewed to consider whether the conclusions from chapter 2 were valid, ie laser radiation issues were readily addressed using the guidance and standards available and that the main safety issues related to the non-beam aspects and practical risk assessment.

It was necessary to analyse each of the events using a common format. This would also highlight areas which needed further investigation. A description of each of the events studied is presented in Appendix B.

The inclusion of an event in this chapter does not necessarily imply that the public were exposed to an unacceptable risk. Of equal concern was whether the laser company could quantify the hazards and therefore make a judgement about the magnitude of any risks. As already stated in Chapter 1, the average family attending an event provided for their entertainment assumes that their safety is assured.

Each of the events is identified by a letter (A-H), for reference in the summary table. An outline of the events is presented in table 3.8

Table 3.8 Outline of Laser Events

Event	Description
A	Outdoor Classical Laser and Firework Concert
B	Outdoor Classical Laser and Firework Concert
C	Outdoor Display at a Marina
D	Drive-In Movie and Laser Show
E	Trade Exhibition
F	Trade Conference
G	Medical Laser Exhibition
H	Laser Tag Game

3.3 Analysis of Laser Events

Factors of interest in analysing the events described in Appendix B include whether the event could be assessed in advance, ie whether adequate documentation was available; whether the event could be assessed on the day, but before the start time of the event; and whether the risks were adequately assessed and/or controlled.

None of the laser companies involved in the events were able to supply adequate information in advance to enable a judgement to be made. Although an appendix 3 to PM19 was supplied for seven of the eight events, the information was either not appropriate, incomplete or wrong. In all these cases, the companies considered that the information they had supplied was adequate and events had been approved in the past on the basis of similar paperwork.

Some of the assessments were carried out with either Environmental Health Officers or venue safety managers. They did not understand the information they were being provided with. In all cases, proactive consideration of safety was considered by the laser company staff to be detrimental to their work. There appeared to be an ethos that raising safety issues would imply an unacceptable risk and this was not what the promoters wished to hear.

There were several cases of the actual event not matching the paperwork provided. In one case (event A), the arrangement for the stage was changed on the day. At another (event C) further construction work took place after the initial assessment, which altered the risks.

Practical preparation and planning prior to the events appeared to be limited. It was usual for the equipment to arrive on site and then to be constructed into a laser display system using a range of components. Generally, inadequate time was allowed for construction and alignment to take place.

At most of the events, audience exposure to the laser radiation was either planned or reasonably foreseeable. None of the laser companies had the ability to assess the magnitude of the hazard, or the risk of injuries taking place. All laser companies were experienced, in that they had undertaken many events previously. They appeared to rely on a lack of reported incidents from previous events to justify the lack of risk.

Whilst the quantification of the laser radiation hazard was an obvious issue, the associated hazards often had more immediate impact. Outdoor events in particular suffered the problems from trying to operate essentially laboratory equipment in a relatively hostile environment. Water and electrical power were always a problem. Since they are so vital to the operation of the laser display, and must be an issue at most outdoor laser events, it was astonishing how surprised the laser company staff appeared to be that they experienced problems.

The enforcing officer or venue safety manager generally did not have experience of assessing laser events. However, rather than consider the issues they should have been familiar with, such as electrical and mechanical safety, they considered the laser event to be completely different. The laser radiation safety issue may have been minor compared with the risk of electrocution and working at height.

The laser companies were normally working alongside other sectors of the industry, such as fireworks companies, stage construction companies, and lighting and sound engineers.

These sectors generally presented a professional (to the uninitiated) image with good preparation and equipment that appeared to be designed and constructed for the environment in which they were intended to work. The staff from these other companies generally considered the laser companies to present an amateur image and, in some cases, considered them a danger to everyone working in the vicinity.

None of the events fully complied with the requirements of PM19.

3.4 Conclusions

Table 3.9 summarises the eight events assessed and brings together the common factors which needed to be investigated further. Consideration is given to the paperwork supplied by the laser company, such as the PM19 Appendix 3 (HSE 1980).

The selected examples reported here demonstrate that exposure in contravention of the then Health and Safety Executive Guidance was occurring. There were no events attended by the author where everything was satisfactory. There was a wide range of knowledge amongst Environmental Health Officers (EHOs). The laser companies have been known to use this to their advantage. However, further research was required to identify the extent of the involvement of EHOs with laser displays. It would not be reasonable to expect EHOs to be experts in assessing laser displays if they are rarely required to assess them. A more effective use of public money would be to seek assistance from a third party when necessary. It was necessary to survey the enforcing officers to determined the extent of their involvement in laser displays. However, it was found that all of the EHOs had expertise in the non-laser-radiation hazards, but because they were dealing with a laser product did not always use this expertise to work through the problem systematically. They saw the use of lasers as being special.

The stage at which the EHO became involved in the event, and the stage at which they sought external advice, also had a bearing on how the final event could be influenced to ensure that the risks were minimised.

The human factor has been shown to be a major component in the display events discussed, but engineering and administrative controls were also found to be inadequate.

It was clear that some of the laser companies wished to provide shows with the risk to everyone minimised. However, their technical ability to do this was limited. In other instances, the desire to expose personnel directly with the laser radiation was driven by the perceived customer desire for this. It is likely that this ethos will only be overcome by the laser companies demonstrating that they can produce more effective shows without the need for the beams to go into audience areas. This requires an understanding of the eye's response to laser radiation in terms of visual perception rather than health effects.

A common comment from the laser display operators was that the enforcing officers did not understand the 'special' problems associated with the laser display industry. Equally, the enforcing officers considered the laser display companies unhelpful. The root of the problem appeared to be an inconsistent approach to assessing laser displays throughout the UK, possibly due to the lack of specific legislation. This was generating friction because operators found it difficult to understand why a show could be considered acceptable in one location, but not in another. There was also no recognised approach to either tackling or assessing the risks from the activity.

It is obvious from these assessments that there is a wide gulf between the laser display companies and the enforcing officers.

The methodology used to progress an improvement to the level of laser safety was to understand the tasks involved in putting on a laser display (including an understanding of the technology), identify whether it was possible to develop a protocol for identifying the hazards, quantifying these hazards, assessing the risks and presenting the conclusions.

Table 3.9 Summary of Common Factors from the Laser Events

Event	A	B	C	D	E	F	G	H
EHO Experienced?	N*	?	N*	N*	N/A	N/A	N/A	N/A
Collaboration?	P	P	P	P	N	N	P	N
Risk Assessment?	N	N	N	N	N	N	N	N
Training - use	Y	Y	Y	Y	N/A	Y	N/A	N/A
Training - safety	N	N	N	N	N	N	N	N
Mechanical Stability	N	N	N	Y	N	Y	N/A	N/A
Goggles Available	N	Y	N	N	N/A	N	N/A	N
Written Procedures	N	N	N	N	N	N	N	N
Laser Controlled Area	N	N	N	N	N/A	N	N/A	N/A
App 3 PM19 Supplied?	Y	Y	Y	Y	Y	Y	Y	N
App 3 PM19 Adequate?	N	N	N	N	N	N	N	N/A
EMC Problem?	Y	N	N	N	N/A	N	N/A	N
Operation/control	Y	Y	Y	Y	N/A	Y	N/A	N/A
Human Factors	Y	Y	Y	Y	Y	Y	Y	Y

Notes: Y = Yes, N = No, ? = not known, P = Partial, N/A = not applicable

*laser safety support provided at the request of the EHO

4. Surveys

4.1 Introduction

Chapter 3 outlined the problems with a small number of events. This showed that there was limited knowledge about laser radiation issues and laser displays amongst enforcing officers. Laser display companies were perhaps using this, but were also unable to demonstrate that the displays they were putting on were safe, and venue managers generally assumed that the laser display companies knew their business. In order to acquire a better understanding of the magnitude of this problem, surveys were carried out of the three identified groups. It was recognised that some groups would be more forthcoming with information than others.

4.2 Enforcing Officers

Local authorities are the enforcing authority for safety legislation at most entertainment venues and this function is normally performed by Environment Health Officers. Therefore, the Chartered Institute of Environmental Health was approached for support for a survey of Chief Officers. A questionnaire (Appendix C) was prepared using multiple choice, closed and open questions, and peer reviewed before distribution by the Epidemiology Group at NRPB. It was then sent to all pre-April 1996 local authorities (483) on the UK mainland and Northern Ireland. The respondents were at either Principal or Chief Environmental Health Officer level. Therefore, it can be assumed that the respondent either was fully aware of the experience and training requirements of their staff or were in a position to acquire such information.

4.2.1 Number of Laser Displays

Out of 483 local authorities canvassed, 277 sent replies, although one was anonymous. This represents a return of 57.3%. Of these 277 returns, 92 (33.2%) had dealt with laser displays in the preceding twelve months, covering 244 identified uses of lasers. The anonymous reply had not dealt with a laser display. The distribution of replies by county is presented in Table 4.1. The distribution of the number of displays dealt with is shown in figure 4.1 and tabulated by type in table 4.2

Table 4.1 Distribution of Questionnaire Replies by County

County	Replies/No. of Districts	No. of Laser Displays	County	Replies/No. of Districts	No. of Laser Displays
Avon	4/6	6	Humberside	5/9	0
Beds	2/4	0	Kent	8/14	3
Berkshire	4/6	1	Lancs	9/14	5
Borders	1/4	0	Leics	6/9	3
Bucks	4/6	13	Lincs	4/7	6
Cambs	2/6	1	Lothian	2/4	6
Central	2/3	0	Merseyside	3/5	1
Cheshire	5/8	3	Mid Glamorgan	3/6	0
Cleveland	2/4	0	Norfolk	5/7	10
Clwyd	4/6	1	N Yorks	4/8	1
Cornwall	3/6	1	Northants	4/7	2
Cumbria	2/6	2	N Ireland	10/26	3
Derbyshire	7/10	2	Northumberland	6/6	2
Devon	9/10	5	Notts	2/8	2
Dorset	4/8	0	Oxon	4/5	6
Dumfries	1/4	0	Powys	3/3	0
Durham	5/8	0	Shropshire	5/6	4
Dyfed	5/6	6	Somerset	2/5	1
E Sussex	6/7	23	S Glamorgan	2/2	2
Essex	9/14	17	S Yorks	1/4	0
Fife	1/3	0	Staffs	7/9	8
Gloucs	2/6	0	Strathclyde	6/19	4
Grampian	3/5	0	Suffolk	5/7	3
Greater London	17/33	48	Surrey	9/11	10
G Manchester	5/10	4	Tayside	3/5	0
Gwent	3/5	1	Tyne & Wear	3/5	0
Gwynedd	1/5	0	Warwickshire	4/5	3
Hampshire	7/13	2	W Glamorgan	2/4	0
Hereford	6/9	2	W Midlands	5/7	9
Herts	3/10	2	W Sussex	5/7	2
Highland	3/8	0	W Yorks	3/5	3
			Wiltshire	4/5	4

Table 4.2 Breakdown of Laser Displays Dealt with by Local Authorities

No. of Displays	No. of LAs	Perm. Indoor	Perm. Outdoor	Temp. Indoor	Temp. Outdoor
1	41	7	1	16	18
2	19	13	1	14	10
3	12	10	0	17	10
4	5	0	1	8	11
5	4	7	2	8	3
6	6	5	0	18	10
7	0	0	0	0	0
8	2	3	0	10	3
9	0	0	0	0	0
10	1	0	0	10	0
11	0	0	0	0	0
12	0	0	0	0	0
13	1	0	0	12	1
14	1	0	0	13	1

58 local authorities (63.0% of those who had dealt with laser displays) provided information on the type of lasers used and this data is presented in figure 4.2. It was recognised that the detailed information relating to particular events may not have been available. However, it could also be concluded that, in some cases, the local authority may not have requested the relevant information at the time.

It can be seen that the majority of lasers displays make use of argon or krypton/argon lasers. The neodymium:YAG laser has just started to appear but, with the smaller size and lower electrical power requirements for diode-pumped Nd: YAG laser than for the gas laser, is likely to increase in popularity. It was interesting that the He-Ne laser still figured highly. It is assumed that these were mainly installed in smaller venues.

Figure 4.1 Number of Laser Displays Assessed by Local Authorities

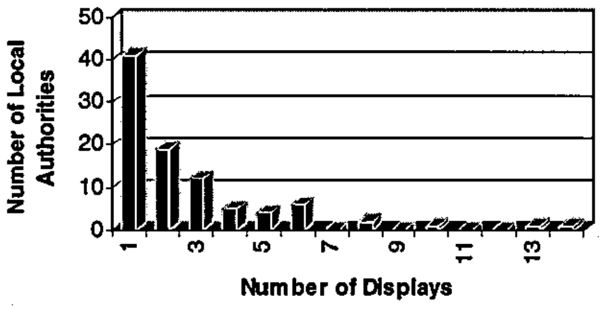
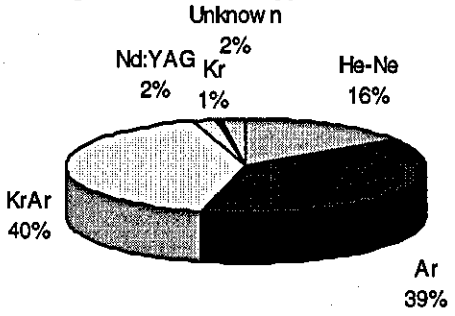


Figure 4.2 Laser Types Assessed



4.2.2 Level of Expertise

The local authorities were asked to judge their level of expertise in dealing with laser displays. They were asked to initially indicate how many staff they had within each of the three categories: No experience; Basic knowledge; and Experienced. Many respondents just ticked the boxes rather than entering numbers. To assist with classifying staff into the three groups 6 questions were provided. Answers to the questions were not required but several forms were returned with answers. None of these had completely correct answers.

The data from the self-assessment of expertise is presented in Table 4.3, divided into those who had dealt with laser displays in the preceding twelve months and those who had not. Where boxes were ticked instead of a number provided, the tick was replaced by 1. Therefore, this data may represent an underestimate of the actual number of individuals.

Table 4.3 Level of Expertise in Local Authorities for Dealing with Laser Displays

Category	Dealt with Laser Displays in Preceding 12 Months?		Total
	No	Yes	
No experience	138	46	184
Basic Experience	102	73	175
Experienced	4	11	15

At the time of the survey the current guidance from the Health and Safety Executive was PM19. Therefore, respondents were asked to report on their familiarity with the document and whether they had a copy of it.

Table 4.4 Familiarity with HSE PM19

Category	Dealt with Laser Displays in Preceding 12 Months?		Total
	No	Yes	
Never heard of it	50	9	59
Know of its existence	159	45	204
Seen forms provided by laser companies	29	35	64
Working knowledge	31	55	86
Detailed knowledge	5	8	13

It was interesting that the number of people who considered themselves experienced at assessing laser displays was more than those who considered that they had a detailed knowledge of PM19.

When asked if they had a copy of PM19, 87.7% of the respondents said that they did. This is broken down into 88.0% of those who had not dealt with a laser display and 96.7% of those who had. The latter group consisting of three local authorities who had dealt with a laser display, without a copy of PM19, although it was not possible to judge whether they felt they had the expertise anyway or were using some other document to assess the display against.

4.2.3 External Assistance

It had been recognised from the author's own experience that local authorities commonly bring in expertise from third parties to assist when necessary. This would be particularly cost-effective for a local authority which may encounter one, or a few, laser displays per year. Therefore, the questionnaire asked who the local authority would turn to for further advice. Six options were given plus an "other". Respondents were encouraged to tick all that applied. The data is presented in Tables 4.5 and 4.6.

Table 4.5 Where would you go for further assistance?

Category	Dealt with Laser Displays in Preceding 12 Months?		Total (out of 277)
	No (out of 185)	Yes (out of 92)	
Other local authority (LA)	129 (69.7%)	40 (43.5%)	169 (61.0%)
Chartered Institute of Environmental Health (CIEH)	70 (37.8%)	20 (21.7%)	90 (32.5%)
Health and Safety Executive (HSE)	164 (88.6%)	77 (83.7%)	241 (87.0%)
NRPB	74 (40.0%)	43 (46.7%)	117 (42.2%)
Loughborough University (LU)	9 (4.9%)	10 (10.9%)	19 (6.9%)
Consultants	24 (13.0%)	17 (18.5%)	41 (14.8%)

All local authorities provided an answer to these questions. Only one said that they would not seek any external advice, citing the Building Control section of the authority as their point of reference. It is not known if the officers in Building Control seek external advice in this instance.

Table 4.6 Specified replies to "Other"

Category	No. displays in 12 months	Who else did they specify?
Other University	0 3	CIEH, HSE LA, CIEH, HSE, NRPB, LU, Consultant
Health & Safety Agency Northern Ireland	0	LA
Building Control	3 1	Consultant None
Laser Display Company	13	LA, HSE
Institute of Lighting Engineers	0	LA, HSE
Royal Environmental Health Institute of Scotland	0 0	LA, CIEH, HSE, NRPB LA, HSE
As Appropriate	0	LA, CIEH, HSE, NRPB, LU, Consultant

Perhaps the most significant answer here was the local authority who used a laser display company to provide them with consultancy support and the number of laser displays assessed on behalf of that local authority (13). From the experience shown in chapter 3, questions must be raised on the competence of the laser display company to provide such advice.

4.2.4 Training

The preceding sections suggest that the necessary expertise to assess laser displays does not exist in most local authorities. As has already been stated, it is valid for local authorities to bring in external assistance when required. Indeed, this may be the most efficient and cost-effective use of limited resources within local authorities. However, the questionnaire asked if local authorities required training and, if so, to what level and in what format.

236 of the 277 respondents (85.2%) said that they would like some form of training for their staff. Of these, 149 (out of 185) had not dealt with a laser display in the previous twelve months and 87 (of 92) had. Of those that said they did not need training 36 had not dealt with a laser display and 5 had.

The levels of training suggested were:

- Overview seminar (up to 2 hours)
- Basic awareness (1 day)
- Working knowledge (2 days)
- Detailed knowledge (4 days)

There was also the option to tick "I do not have enough knowledge to judge". A number of respondents used this box in addition to other boxes. The number of ticks for each option is presented in Table 4.7.

Table 4.7 Training Requirements

Category	Dealt with Laser Displays in Preceding 12 Months?		Total (out of 277)
	No (out of 185)	Yes (out of 92)	
Overview seminar	40 (21.6%)	12 (13.0%)	52 (18.8%)
Basic awareness	102 (55.1%)	57 (62.0%)	159 (57.4%)
Working knowledge	61 (33.0%)	53 (57.6%)	114 (41.2%)
Detailed knowledge	9 (4.9%)	11 (12.0%)	20 (7.2%)
I do not know enough to judge	21 (11.4%)	4 (4.3%)	25 (9.0%)

Four local authorities identified a need for training at all four levels, thirteen identified a need at three levels (11 at the lower three and 2 at the upper three). This simple analysis shows that there is a desire for training from local authority staff. However, it is recognised that this may be positively biased. The wish to pay for, and spare the time to attend, training may not be borne out in practice.

The questionnaire asked which format the respondent would like to see the training take: formal lectures only; lectures supported by syndicate exercises; or a workshop (worked examples with demonstrations). 231 replies were received and many specified more than one choice of format. Since many local authorities suggested they required several levels of training, this is reasonable. The counts were as follows: formal lectures only - 27; lectures supported by syndicate exercises - 61; and workshop - 173. This is based on an equal cost for all options and the bias is perhaps as expected. The respondents were then asked to choose again if the cost was weighted 1:1.5:2 for the three options. 168 replies were received to this, again with several local authorities choosing more than one option. The counts were shifted towards the lectures only as follows: formal lectures only - 33; lectures supported by syndicate exercises - 63; and workshop - 88. Although it was not possible to identify this from the data, it is possible that the bias towards the workshop option would have come from more experienced staff who had attended training in a similar format.

The next question considered how far the respondent would be prepared to send their staff for training and to put these in order of preference. Options given were:

1. Anywhere in UK
2. A regional centre - eg Glasgow, Leeds or Oxford
3. Up to 100 miles
4. Up to 50 miles
5. Within the County of this local authority only.

It may be expected that all respondents would choose option 5. However, from the author's experience of training, more experienced staff tend to prefer to be trained with personnel from outside their immediate work environment. This also has the benefit of being remote from the disruptions of the office.

There were 234 replies to this question (giving at least one preference). The data is presented in Table 4.8.

Table 4.8 Preferred distances to travel for training

Option	1st	2nd	3rd	4th	5th
1	0 (0%)	0	0	6	125
2	41 (17.5%)	20	25	81	0
3	28 (12.0%)	14	90	34	0
4	48 (20.5%)	110	19	0	0
5	117 (50.0%)	13	7	11	6

Members of the Chartered Institute of Environmental Health have a Continuous Professional Development (CPD) scheme (CIEH 1996). Although there is currently no requirement for formal examinations following training, a question was asked to determine if the respondents felt that any training should be followed by a formal examination. 63 of the 236 respondents who required training said yes (26.7%). These were roughly equally divided between those who had dealt with laser displays in the preceding twelve months (29) and those who had not (34). Of these 63, 62 answered yes to the question on whether the examination should be accredited. Eleven chose more than one of the options. The data is presented in Table 4.9. Those respondents who replied "other" did not specify any of the given options. Generally, the written answer given by these respondents suggested that they did not have a preference or the accreditation should be given by whoever gives the training. One respondent was more specific and suggested the Royal Environmental Health Institute of Scotland.

Table 4.9 Preference for Accreditation Body for Examination

Category	Dealt with Laser Displays in Preceding 12 Months?		Total (out of 62)
	No (out of 34)	Yes (out of 28)	
Chartered Institute of Environmental Health	18 (52.9%)	7 (25.0%)	25 (40.3%)
Health and Safety Executive	8 (23.5%)	6 (21.4%)	14 (22.6%)
NRPB	12 (35.3%)	13 (46.4%)	25 (40.3%)
Loughborough University	3 (8.8%)	0 (0%)	3 (4.8%)
Other	2 (5.9%)	4 (14.3%)	6 (9.7%)

4.2.5 Specific Comments

Six of the 277 respondents made specific comments on the returned questionnaires:

"Hands on experience with practical procedures is important."

"I have attended a number of training events on display lasers. Usually the physics and technology is taught very well but the organisers have a very poor understanding of the role of inspectors and the application of the law. The status of PM19 and the role of BS or ISO Standards is also misunderstood. EHOs do not normally have to make PM19 calculations themselves. I would, however, welcome a course which helped in the interpretation of calculations and demonstrated clear pitfalls. I would be very disappointed by another course where the role of the law and the enforcer was misunderstood."

"A formal examination would put the price up too much."

"The need to use expertise is too infrequent - training would be out of date too quickly."

"Would not be able to justify training in our own district - possibly as part of a Liaison Group involving other local authorities."

"Level of use of lasers in the types of premises currently in use in this District doesn't justify specialist training. I buy in expertise where needed and we are happy to admit we don't know it all! Our premises are changing and so will our training needs."

In summary, these comments support the argument for third-party assistance rather than specific training courses for some local authorities. However, they also suggest that training which has been provided may not be meeting the needs of the local authorities.

4.3 Venue Managers and Laser Display Companies

The questionnaire to the Environmental Health Officers provided a reasonable response. It was considered important to balance these views with those from the entertainment industry. A questionnaire was prepared to assess the knowledge of venue managers, laser display companies and anyone else involved in the industry. This was included with the December 1995 edition of Disco International (O'Hagan et al, 1995) along with a supporting article. A copy of the questionnaire is included as Appendix D. Approximately 8000 copies of the magazine were distributed. No replies were received. There are probably a number of reasons for this, including: suspicion of officialdom, lack of interest, concern over the use of the information, and the requirement to pay return postage or fax costs. Although a reply-paid option had been suggested, the editorial management of the magazine were reluctant to use valuable space for this.

Subsequent to the questionnaire, working relations were developed with a number of laser display companies which allowed measurement techniques to be developed, as described later. Attempts to audit chains of night-clubs on behalf of the holding companies met with a poor response. Most of the data presented in later chapters has been obtained through involvement with the local authorities.

An impromptu survey was carried out of a number of the more established laser display companies during a meeting held at NRPB on 8 January 1997 to launch the Health and

Safety Executive's new guidance, HS(G)95 (HSE 1996a). Ten companies provided replies. Their estimate of the number of fixed and temporary installations taking place in a twelve month period was 554. Those completing the survey considered that they represented about 50% of the market, suggesting about 1100 installations per year. When this figure is compared with the results from the EHO questionnaire (277 laser displays for 57.3 % of the local authorities) this suggests that either the non-responding EHOs are assessing a higher proportion of laser displays or that a significant number are not being assessed. It could also be concluded that the laser display companies are over-estimating the number of installations they undertake per year.

4.4 Training Courses

The enforcing officers had identified a need for training and the data from chapter 3 suggests that both the laser display companies and venues/promoters would also benefit. The case for training the staff from the laser display companies is clear: competent staff should be employed. However, for both the enforcing officers and the venues/promoters the cost of training (and the development of that training through practical experience) needs to be balanced against the benefits of using third parties to provide the detailed assessment.

A one day course will cost the actual course fee, travel and subsistence and time away from work. There will also be a need for further commitment to ensure that the participant applies the knowledge gained and retains any competence. A laser display operator should apply the knowledge on a regular basis and hopefully provide a return on the investment in a reasonably short time. However, for the enforcing officer and venue/promoter, the knowledge may be of benefit in the short term, especially if the purpose of attending the training course was to gain sufficient knowledge to assess a specific event, but of less practical use at other times if the training is not reinforced.

The use of a specialist consultant to provide advice to a local authority for each laser event may be cost effective if the number of events per year in small. Working alongside a consultant may also be an effective means of training an enforcing officer. Another factor which needs to be considered is that the enforcing officer is also likely to be involved with other aspects of the event, such as food safety, hygiene and other health and safety issues. There may also be different parts of the local authority involved with the event where entertainment licensing is covered by someone other than the Environmental Health Officer. A consultant may be able to provide the liaison between the relevant parties and, through experience, know the right questions to ask and, more importantly, know that the answers to these questions are correct.

NRPB and Loughborough University first offered a training course on "Laser Safety in the Entertainment Industry" in August 1994. This was intended as a one-day awareness course for enforcing officers, venue managers, promoters and laser display companies. It was recognised that enforcing officers would have a reasonable appreciation of health and safety, and possibly entertainment, legislation. However, they were unlikely to have much knowledge about the technical aspects of laser displays.

Topics covered in the training included:

- The Use of the Laser
- Details of Laser Display Systems
- Laser Radiation Hazards
- Associated Hazards
- Legislation, Standards and Guidance
- Risk Assessment.

An important aspect of any training course is the feedback received. This is both in the form of experience of the participants and formal reviews. Participants were asked to assess each presentation and provide supporting comments. They were also asked to assess the course overall.

The general comments suggested that the course had provided a useful introduction. However, a number of participants considered that some topics would benefit from a workshop format. Most of the participants asked to be involved with further research into a methodology for assessing laser displays.

Most of the participants on the courses were either enforcing officers or venue managers. It was proving very difficult to attract participants from the laser display community. The conclusions to be drawn from this could include that they considered they did not need the training, the training was not appropriate, or they were not prepared to accept training from persons outside of their industry.

The one day awareness course was obviously meeting some of the needs of the enforcement officers and venue management. These were likely to be persons who wanted an overview of laser displays and sufficient expertise to know when to call in external assistance. This was borne out by requests for advice from the course participants when laser displays required assessment in their geographical areas. The next level to consider was the group who wanted to assess most displays themselves but still be able to appreciate their limitations. This would also hopefully appeal to managers and staff from laser display companies.

In 1996 a series of one day awareness courses were run followed by a one day workshop on assessing laser displays. Four such pairs of courses were run throughout the year and, for the first time these attracted participants from the laser display industry. The loan of laser display equipment and the informal input from the industry assisted greatly in developing a successful training strategy. The introductory day was run essentially the same as the previous courses but the second day included a greater degree of participation, including an assessment of a display using the then Health and Safety Executive guidance, PM 19 (HSE 1980).

Written comments to support numerical assessments suggested that assessing exposure to the laser beam was the greatest concern for the course participants. This is despite this aspect of laser safety being covered by many standard texts and considered by many professionals to be well understood (see Chapter 2). All participants expressed a desire for a methodology for assessing laser displays.

4.5 Summary

It has been possible to get quite a good overview of the current situation regarding local authorities but the laser display industry itself is more guarded.

The large return rate for the local authority questionnaire is likely to be because of the general acceptance of NRPB as an independent organisation which provides assistance to local authorities, for example on radon assessments. The number of laser displays seen by local authorities is smaller than expected. Even if the number seen (244) is multiplied up for the number of local authorities who did not respond (x 483/277) this only represents 425 laser displays per year. Even when taking into account that the local authority is not the only enforcing body, this must be an underestimate. However, the questionnaire would not take into account the number of fixed laser display installations under the local authority's control if they had been installed more than twelve months prior to completion of the questionnaire.

The most significant finding from the local authority questionnaire is the limited capability, within the local authorities who replied, to assess laser displays. Only 15 persons were considered to be experienced in assessing laser safety at such events. It is accepted that many local authorities seek further advice when necessary but it likely that many rely on the expertise of the laser companies. It is particularly interesting that one local authority stated that they use a laser display company to advise them. This particular local authority had dealt with thirteen laser displays in the previous twelve months.

The lack of response from the other side of the industry was disappointing. Some of the reasons are suggested above. However, it does raise the question of how many venues suspect that their laser safety may not pass scrutiny.

The training courses have provided direct contact with a large number of persons involved across the industry from enforcing officers to laser display operators. The value in understanding the technology and the safety issues is ably demonstrated by the end-of-course assessment questionnaires. Written comments and informal discussions suggested that an assessment methodology was required and specific guidance on how to assess the laser radiation hazard. It is significant that many enforcing officers followed up the training with requests for support to assist with laser entertainment events. This demonstrated that the enforcing officers did not feel that the level of training was sufficient to allow them to assess laser displays alone. Due to resource constraints it was not possible to comply with every request, demonstrating the importance of developing a methodology which could at least be used by enforcing officers and others. Such a methodology could assist the person with the first stage of the safety assessment and perhaps identify the point at which further advice should be sought. In essence, they are seeking a practical guidance document which goes further than the limited formal guidance currently available.

5. Quantifying the Laser Radiation Hazard

5.1 Introduction

In many laser display situations there is the potential for exposure to laser radiation. Although there is a great deal of guidance on how to assess laser radiation exposure in the literature (see Chapter 2) this is identified as the one specific area where there is most concern and controversy. Murphy (1997) and Jones (1997) both consider that the practice of audience scanning presents little risk of injury. This is one side of the argument and, it can be argued, is based on at least ten years of practical experience of audience scanning throughout the world. However, the maximum permissible exposure (MPE) levels published in the current laser safety standard in the UK (BSI 1994) are based on considerable research since the first successful demonstration of the laser. UK safety legislation can use the MPE values as a metric against which the risk can be judged: if the MPE is not exceeded then the risk is acceptable, if it is exceeded the risk becomes more unacceptable as the degree of excess is increased.

The former UK guidelines on the use of lasers for entertainment (HSE 1980) included a proforma (appendix 3) which required the laser display company to provide calculations or measurements of exposure levels. In the author's experience such information is either not provided or does not relate to the specific event. It is this lack of information and perceived ability to assess the magnitude of the laser radiation hazard which is of greater concern than whether actual injuries are occurring.

This chapter describes the theoretical and practical assessment of the laser radiation hazard, so-called quantification of the hazard. This process should form an important part of the planning stage of any event. A laser company ought to be capable of undertaking such assessments where the risk of exposure to the hazard is more than remote. This will include the manufacture of the laser product at the company's premises, alignment on site and any reasonably foreseeable audience exposure situations, including intended audience scanning.

Comparisons need to be made with published values for maximum permissible exposure (MPE). The values in BS EN 60825-1: 1994 (BSI 1994) will be used throughout.

5.2 Primary Laser Beam

Generally, the worst case condition will be exposure to the full radiant power of the laser beam as it exits from the laser aperture. In order to compare the exposure situation with the MPE the following parameters are required (assuming the laser radiation is emitted as a continuous wave (cw)):

wavelength
radiant power
beam diameter
exposure duration

If the laser radiation is emitted as a single pulse or a train of pulses then the radiant energy, pulse duration and (if appropriate) pulse repetition rate are required.

The MPE is given in terms of irradiance ($W\ m^{-2}$) or radiant exposure ($J\ m^{-2}$). For visible laser radiation (400 to 700 nm) BS EN 60825-1 uses a limiting aperture of 7mm: if the actual beam diameter is less than 7 mm then the actual radiant power is averaged over a disc of 7 mm diameter. Therefore, in these situations the biological irradiance is less than the physical irradiance. A description of the rationale for this can be found in, for example, Sliney and Wolbarsht (1980, pages 241-242).

It can be reasonably assumed that any exposure to the primary laser beam will be accidental for most of the applications of lasers for display purposes. The exception may be laser tag games. For a single accidental exposure, the primary protection measure, if the exposure is to the eye, will be the aversion response comprising the blink reflex and violent movement of the head. The laser safety standards assume this process in completed within 0.25 s.

5.2.1 Accidental Exposure to a CW Beam

For exposure durations up to 10 s the MPE is independent of wavelength over the wavelength region 400 to 700 nm. For a single accidental exposure the exposure duration can be considered to be 0.25 s (Sliney and Wolbarsht 1980, p 223). Therefore the MPE (taken from Table 6 of BS EN 60825-1) is:

$$MPE = 18\ t^{0.75}\ C_6\ J\ m^{-2} \qquad 5.1$$

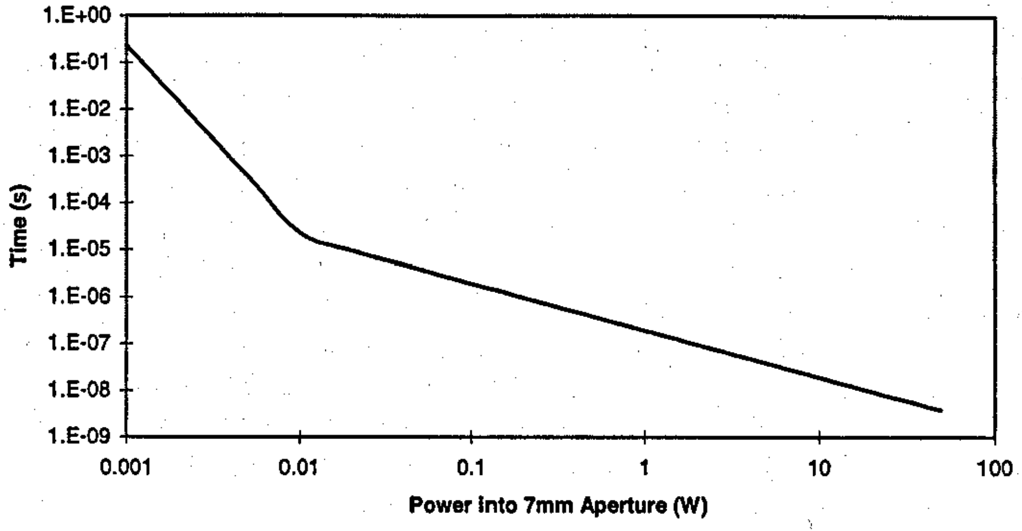
C_6 is a correction factor to be used where the beam is viewed as an extended source and therefore can be set to 1 here. Substituting for t = 0.25 s, the MPE = 6.36 J m^{-2}. This is converted to an irradiance by dividing by the exposure duration, t, to give 25.4 W m^{-2}. If the beam diameter (defined in BS EN 60825-1 as the smallest circle which contains 63% of the total laser power (sub-clause 3.10)) is less than or equal to 7 mm then the maximum radiant power to not exceed the MPE can be calculated:

$$\begin{aligned} P_{max} &= MPE\ x\ Area\ of\ beam \\ &= 25.4\ x\ \frac{\pi}{4}\ (0.007)^2 \qquad 5.2 \\ &= 0.001\ W\ or\ 1\ mW \end{aligned}$$

Therefore, if the radiant power of a cw laser beam exceeds 1 mW, the MPE will be exceeded during an accidental exposure if the beam diameter is less than or equal to 7 mm. The MPE for exposure durations from 1 ns to 18 μs is 5 x 10^{-3} J m^{-2} or 5 x $10^{-3}/t$ W m^{-2}.

The time to exceed the MPE as a function of radiant power into a 7 mm aperture is presented in figure 5.1. It can be seen that even at 10 mW, the time to exceed the MPE is about 25 μs. At 5 W, which is typical of many laser display systems, the time to exceed the MPE is about 40 ns. Any control measure designed to protect the eyes of someone working within the region where the beam diameter is up to 7 mm will have to act within 40 ns for a 5 W laser.

Figure 5.1 Time to Exceed MPE as a Function of Power



A similar assessment can be undertaken for the skin. It is accepted that skin injuries may be considered a tolerable occupational hazard by employees of the laser company but they will not be tolerable to, for example, the audience. The skin MPE values from BS EN 60825-1 are 200 J m^{-2} from 1 ns to 100 ns, and $1.1 \times 10^4 t^{0.25}$ J m^{-2} from 100 ns to 10 s. For exposure durations of 10 s or longer, the MPE is 2000 W m^{-2}. All of these values are constant with wavelength over the region 400 to 700 nm.

The duration of an accidental exposure to the skin is less easy to define. One consideration is how long someone remains in the same position, another will be the type of activity they are carrying out. Exposure durations of either 10 s or 100 s could be justified. The limiting aperture for the skin over the visible wavelength region is 3.5 mm (BSI 1994, Table 7). For both 10 s and 100 s the MPE is the same - 2000 W m^{-2}. The maximum radiant power into 3.5 mm from this MPE is 19 mW. The time to exceed the relevant MPE as a function of radiant power into 3.5 mm is presented in figure 5.2. For a 5 W laser, the maximum exposure duration is about 6 ms.

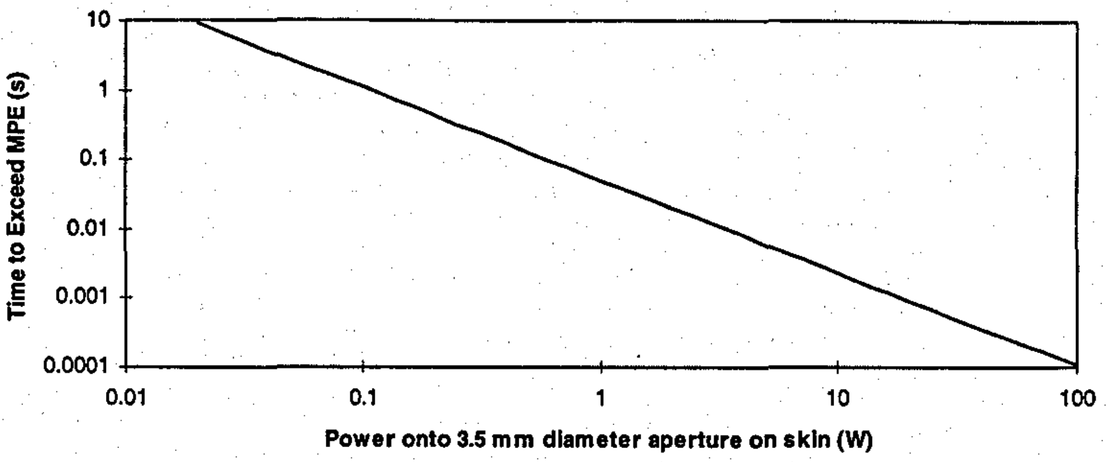


Figure 5.2 Time to Exceed MPE as a Function of Power on Skin

5.2.2 Accidental Exposure to a Single Pulse

If the laser emits a single pulse of laser radiation, where the duration of the pulse (defined as the time between the half peak power points at the leading and trailing edges of a pulse (BS EN 60825-1 sub-clause 3.60)) is 0.25 s or less, the treatment of the MPE is similar to the cw situation except that the pulse duration is used for the exposure duration. It is then possible to calculate if an exposure to the pulse, either received in the eye or on the skin, will exceed the MPE.

5.2.3 Accidental Exposure to a Train of Pulses

Exposure to a train (or series) of pulses could result from the output of a pulsed laser or a scanned pattern. BS EN 60825-1 requires a three-stage process to determine the applicable MPE (sub-clause 13.3) for laser radiation in the visible region where the target is the eye. The analysis here will be carried out for pulsed laser emission: scanned beams will be considered later.

Two pulsed lasers are likely to gain prominence in the entertainment industry: the copper vapour laser (inherently pulsed); and the neodymium:YAG which is occasionally used Q-switched.

The three stages for determining the MPE are as follows:

1. determine the MPE for a single pulse
2. apply a correction factor to the single pulse MPE (termed C_5 in BS EN 60825-1) which is $N^{-0.25}$, where N is the number of pulses in the exposure duration. This will reduce the single pulse MPE and the resultant is termed the "reduced single pulse MPE"
3. determine the MPE for the exposure duration (termed the "average MPE") and apply this to each pulse.

The applicable MPE is the most restrictive of the three. However, if the MPE falls below what would have been applicable for continuous exposure at the same peak power then the MPE for continuous exposure may be used. An example of this would be exposure to a pulsed laser with a peak pulse radiant power of 0.95 mW for an exposure duration of 0.25 s. The reduced single pulse MPE could be more restrictive than what would have been applicable had the beam been on all of the time.

Typical operating parameters for a copper vapour laser are (Hecht 1992):

Pulse duration:	10 ns
Pulse rate:	10 kHz

The exposure duration will depend on the circumstances. Here, an accidental exposure of someone close to the laser will be considered, such as the laser operator during alignment. Therefore, it will be reasonable to assume 0.25 s. This exposure duration will be termed T, whereas the pulse duration will be t. The first stage is to calculate the MPE for the single pulse. Table 6 of BS EN 60825-1 gives an MPE of 5×10^{-3} J m^{-2} for intrabeam viewing, for a 10 ns pulse. The number of pulses, N, in T is given by the pulse rate (in Hz) divided by 4, which equals 2500. $N^{-0.25} = 0.1414$. Therefore, the reduced single pulse MPE = $0.1414 \times 5 \times 10^{-3} = 7.07 \times 10^{-4}$ J m^{-2}. The average MPE for an exposure duration of 0.25 s is $18 \times T^{0.75} = 6.36$ J m^{-2}. This is divided between the individual pulses, ie $6.36/N = 6.36/2500 = 2.54 \times 10^{-3}$ J m^{-2}. It can be seen that the most restrictive MPE is the reduced single pulse MPE, 7.07×10^{-4} J m^{-2}.

The initial beam diameters from copper vapour lasers tend to be in the region of 20 to 80 mm. Therefore, they will already be larger than the limiting aperture of 7 mm. Assuming a beam diameter of 20 mm, with the energy distributed equally across the diameter of the beam, it is possible to determine the maximum radiant exposure that can be emitted before the MPE is exceeded. This is determined from the MPE multiplied by the area of the beam (since the beam diameter is greater than 7 mm): $7.07 \times 10^{-4} \times \pi/4 \times (0.02)^2 = 2.22 \times 10^{-7}$ J. For a pulse duration of 10 ns, this represents a peak power of 22.2 W. This should be compared with typical devices which produce a peak power of 250 kW or over 10,000 times greater. Therefore, it can be concluded that an exposure to the primary beam from a copper vapour laser is likely to cause serious eye damage in a short period of time.

Many suppliers of pulsed lasers quote average power and not peak pulse power. Using the above example, the average power would be quoted as 25 W, or just above the MPE. No account would be taken of the high peak power delivered in each 10 ns pulse. It is therefore important for those who use pulsed output lasers to understand the significance of the average power compared with the peak power. A failure to understand this issue could result in persons exposed to the beam being at considerable risk of eye injuries: it is like being sprayed by a machine gun which, if it is scanned past you MAY not result in injury (or worse). However, if the bullet (pulse) happens to occur where the person is, the probability of interaction is high. Expressing the output of the laser in terms of energy per pulse, and a knowledge of the area, will permit a direct comparison with the appropriate MPE per pulse.

It is concluded that pulsed lasers should not be used for entertainment applications unless adequate control measures are in place to ensure that people cannot be exposed to the beam.

5.3 Nominal Ocular Hazard Distance

An important part of the risk assessment for the use of lasers in the entertainment industry is the distance at which they present a risk of exceeding the MPE, and therefore the risk of injury. Generally, the eye is the critical organ and therefore the analysis here will concentrate on the distance at which the irradiance or radiant exposure equals the MPE, the so-called nominal ocular hazard distance (NOHD). A similar analysis is required where the skin is the critical organ, for example during alignment work where protective eyewear is worn or for some performer exposures.

The NOHD is calculated from a knowledge of the applicable MPE, the beam divergence, the initial beam diameter and the radiant power or energy of the laser. The MPE and the output of the laser must be in similar quantities, ie if the MPE is in terms of irradiance, the output of the laser must be in terms of radiant power.

In general the diameter, d, of the laser beam at a distance, D, from the aperture is given by the expression:

$$d = a + \phi D \qquad 5.3$$

where a is the initial beam diameter and ϕ is the full angle beam divergence. This expression is valid where ϕ is small and measured in radians such that $\tan(\phi) \approx \phi$. The irradiance at distance D is determined from the radiant power, P, divided by the area of the beam at D:

$$Irradiance = \frac{P}{\frac{\pi}{4} d^2} \qquad 5.4$$

At the NOHD, the irradiance will equal the MPE. Therefore, by substituting for d from equation 5.3, and rearranging with D = NOHD:

$$NOHD = \frac{\sqrt{\frac{4 \, x \, P}{\pi \, x \, MPE}} - a}{\phi} \qquad 5.5$$

Equation 5.5 can be used to determine the NOHD for any laser used in the entertainment industry provided all of the parameters are known. Therefore, it is fundamental to any risk assessment that these parameters are known or reasonable worst-case assumptions can be made. No account is taken here of the effect of air, or smoke, attenuation. The former can generally be ignored over the distances used in entertainment applications. Smoke or vapour effects may attenuate the laser radiation but the effect may not be consistent with time. For these reason it is recommended that no correction factor is applied.

NOHD values for a number of parameters are presented in Table 5.1 for a single accidental exposure to a cw beam. The applicable MPE is 25.4 W m^{-2}. The initial beam diameter, a, has been set to zero since, with the distances generally involved, this represents a small error on the side of safety.

Table 5.1 NOHD as a Function of Radiant Power and Beam Divergence for a Single Accidental Exposure to a cw Beam

Radiant Power → Divergence ↓	100 mW	1 W	10 W
1 mrad	71 m	224 m	708 m
2 mrad	36 m	112 m	354 m
5 mrad	15 m	45 m	142 m

The figure of 224 m at a radiant power of 1 W with a beam divergence of 1 mrad can be used to relate to the NOHD at any other radiant power and divergence (assuming that the effect of the initial beam diameter can be neglected). First the NOHD should be corrected for the actual radiant power by multiplying the distance by the square root of the actual radiant power (measured in watts). This is then divided by the actual beam divergence in milliradians. Therefore, the NOHD for a 10 W laser with a beam divergence of 5 milliradians is 224 x √10/ 5 = 142 m, which agrees with the figure in

Table 5.1. Note that the NOHD should always be rounded up. Generally, this will be to the nearest metre.

The NOHD calculations demonstrate that lasers typically used in the entertainment industry present a risk of eye injury over considerable distances, often comparable or greater than the dimensions of the venue. In military applications where laser beams are intended to travel considerable distances, for example for missile guidance or range-finding, corrections factors have to be applied for air attenuation of the beam and potential scintillation (Sliney and Wolbarsht 1980, Chapter 13). These are not considered appropriate for the entertainment industry since the uncertainties do not justify the effort in determining the correction factors.

5.4 Nominal Skin Hazard Distance

Generally, the eye is the critical organ when considering exposure to visible laser radiation. However, there may be circumstances where the eye is protected, for example by protective eyewear, or where performers may be intentionally exposed on the body, well away from the eyes. It is therefore important to quantify the hazard under such exposure conditions.

MPE values for the skin are presented in Table 8 of BS EN 60825-1. As described above, an accidental exposure duration to a cw laser beam is less easy to define than for the eye exposure situation. A reasonable value to use is 10 s since it is unlikely that anyone would normally stay in a fixed position for longer than this under the exposure conditions considered. A member of the audience may remain stationary for the duration of the show, but this is unlikely. However, for this critical group the risk to the eyes is likely to be greater than that to the skin.

The MPE for a single 10 s accidental exposure to a visible laser beam is 2000 W m^{-2}. Equation 5.5 can be re-written for the nominal skin hazard distance (NSHD) and the data is presented in Table 5.2 using similar parameters to Table 5.1.

Table 5.2 NSHD as a Function of Radiant Power and Beam Divergence for a Single Accidental Exposure to a cw beam

Radiant Power→ Divergence↓	100 mW	1 W	10 W
1 mrad	8 m	26 m	80 m
2 mrad	4 m	13 m	40 m
5 mrad	2 m	6 m	16 m

Again, the reference value of NSHD for 1 W and 1 milliradian can be used to determine the NSHD at other radiant powers and divergences if the initial beam diameter can be ignored.

5.5 Scanned Laser Beams

5.5.1 Introduction

As described in appendix A, graphical images are produced by a number of methods, but most commonly by the action of two mirrors on orthogonally-mounted galvanometers. A scanned laser beam will appear as a pulse of laser radiation as it passes the eye. If the scan parameters are known then the level of exposure to scanned beams can be assessed. This can be followed through to a calculation of NOHD and NSHD for each effect. The assessment of the scanned effects assumes that the scanning system is operating correctly. If any single failure mode could result in a stationary laser beam then the NOHD and NSHD should be based on the direct beam assessments in 5.2 to 5.4, above.

In many cases the exact parameters for a given scanned effect will not be known. Where they are known, they may only relate to a single part of the scanned effect. The analyses presented in this section will assume parameters in order to present the quantification process.

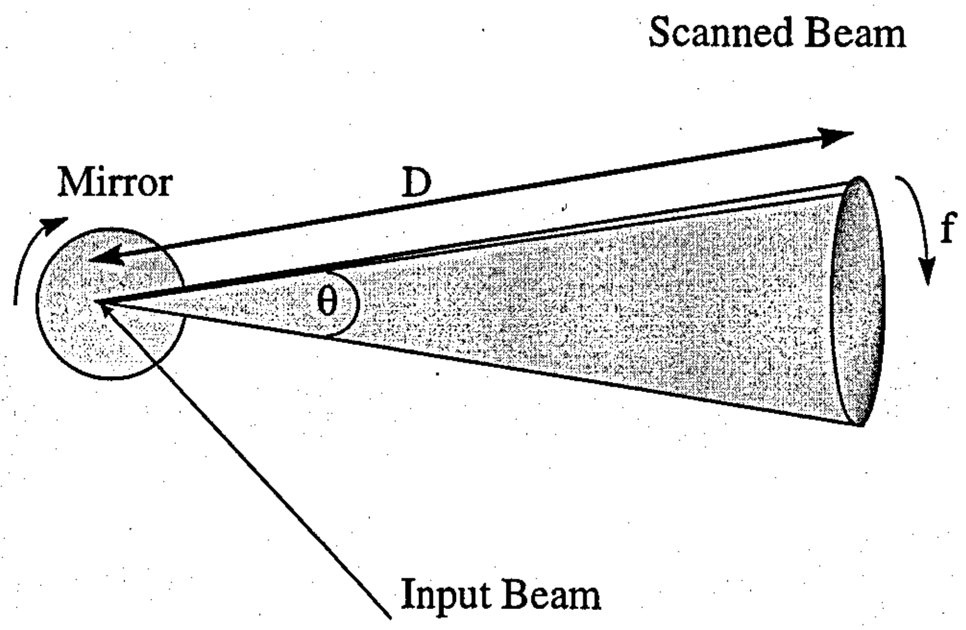
5.5.2 Methods

A theoretical analysis of scanned laser beams is developed and this is compared with measurements from a number of actual scan patterns.

5.5.3 Cone Scan from a Cone Spinner

The simplest, and most reproducible, scanned effect is that produced from a laser beam incident on a mirror mounted on the end of the shaft of a rotating motor. The scanned image will be a circle on a screen and will be perceived as a cone if the beam is made visible in the environment. It is recognised that similar effects can be produced by the use of, for example, galvanometers. However, as will be discussed later, the analysis of the exposure conditions can be more involved than with a cone spinner.

Figure 5.3 Cone Spinner



A diagram of the geometry of the exposure condition from a cone spinner is shown in figure 5.3. Relevant parameters are:

radiant power of the laser, P (W)
beam divergence, from the mirror, ϕ (radians)
initial beam diameter, at the mirror, a (m)
scan speed, f (Hz)
scan full angle, Θ (degrees)
distance of interest, D (m)
maximum permissible exposure, MPE (W m^{-2})

The exposure condition, or time of exposure, needs to be determined at D, assuming a limiting aperture for the eye of 7 mm.

The diameter of the beam at distance, D, is given by equation 5.3. The irradiance at D is given by:

$$Irradiance = \frac{4 \times P}{\pi(a + D\phi)^2} \qquad 5.6$$

The beam will trace out a circular path at D. The diameter of the scan is given by D sin(Θ). The approximation of taking the sine of the scan full angle, as shown in figure 5.3 represents an error of less than 1% up to a scan full angle of 16°. Therefore, the circumference of the scanned pattern will be:

$$Circumference = \pi D \sin(\Theta) \qquad 5.7$$

The speed of the beam will be f multiplied by the circumference. The exposure duration can then be determined, ie the time taken for the beam of the given diameter to cross a 7 mm aperture. The total exposure duration will be the time taken to travel 7 mm plus the diameter of the beam, the largest duration generally being when the centre section of the beam passes the aperture. However, the beam diameter has already been quoted using an assumption, ie, for a Gaussian beam profile, the point at which the irradiance reaches 1/e of the central peak value (BS EN 60825-1 sub-clause 3.10). The pulse duration is defined as the time between the half peak power points on the leading and trailing edges of a pulse (BS EN 60825-1 sub-clause 3.60). If the pulses had been produced from, for example, a pulsed laser, then the rise time of the pulse is generally short compared with the pulse duration. However, in the scanned example, the rise time may be comparable with the pulse duration. The following argument justifies the use of the full width at half maximum (FWHM) value in most circumstances.

Assuming the beam profile is such that the irradiance is constant, ie a flat-topped beam with a square cross section, and that the beam is larger than the detector, which also has a square cross-section, the exposure situation will be as presented in figure 5.4. The signal will increase linearly as the beam leading edge is scanned across the detector. Whilst the detector is completely covered by the beam, the detector output will be constant and then fall linearly as the trailing edge passes over the detector. Taking the FWHM points and projecting them down to the time axis, the area outside the FWHM points equals the area deficit between the FWHM points and the peak value. Therefore, it would be reasonable to assume that the exposure consisted of a pulse at the peak power for the FWHM exposure duration.

Figure 5.4 Irradiance as a Function of Time for a Square Profile Beam

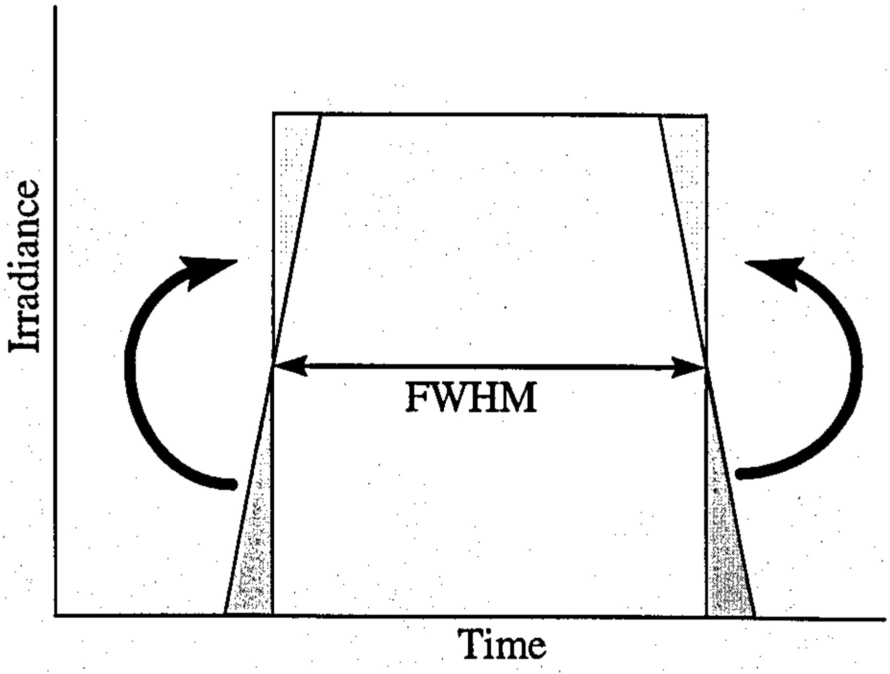
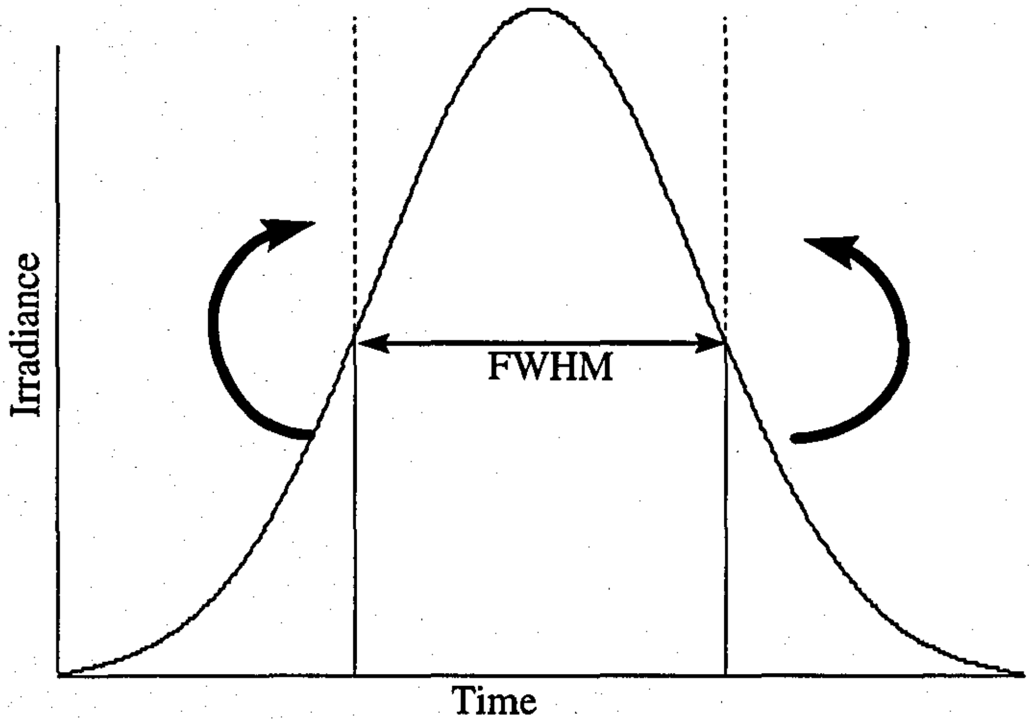


Figure 5.5 Gaussian Beam Across Small Detector



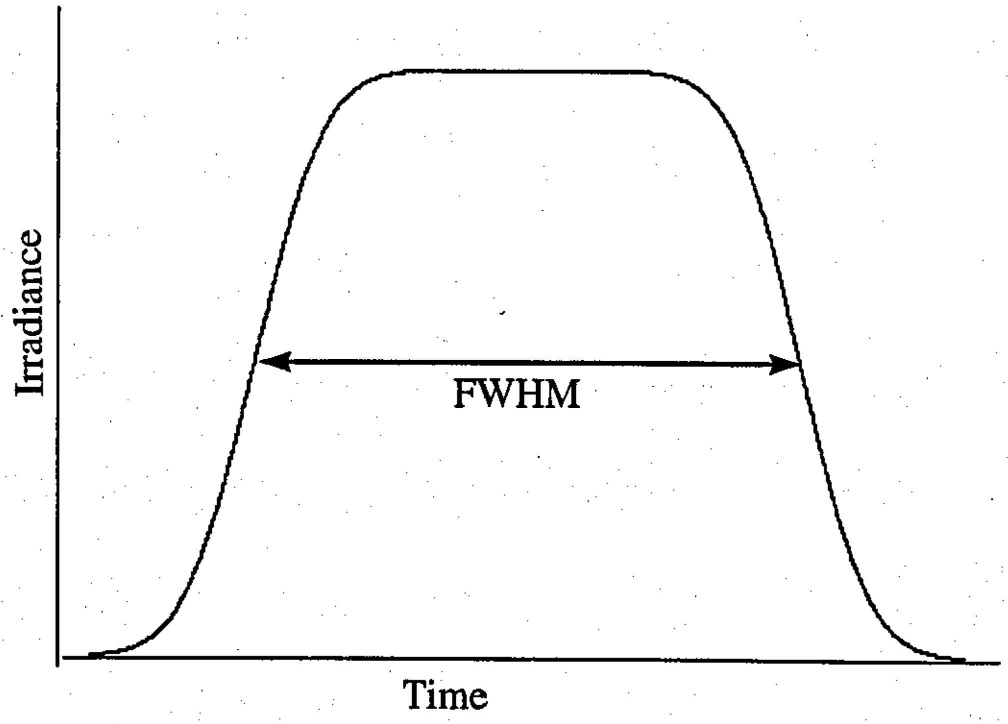
In the actual exposure situation where the beam profile is either Gaussian or a more complex mode, and the detector has a circular cross-section, a similar argument can be used (figure 5.5). The area from the half maximum out to the 3 σ point is approximately 34% greater than the area deficit between the half maximum point and the peak. The use of a detector which is much smaller than the beam width is an effective beam profiling tool when the beam is scanned across the detector face.

If the diameter of the laser beam is much smaller than the diameter of the detector, then the irradiance will be constant as a function of time while the beam crosses the detector (assuming a constant spatial response) even though the beam profile is not flat. The leading and trailing edge of the irradiance as the beam enters the detector aperture and exits from the aperture should approximate the integral of the beam profile. Figure 5.6 is a plot of a Gaussian curve (normal distribution) integrated from 3 σ to -3 σ to simulate the beam passing onto the detector, a constant region where the whole of the beam (within $\pm 3\ \sigma$) passes across the face of the detector and then the inverse of the integral as the beam crosses the edge of the detector. This simulation assumes a beam diameter, specified at the 1/e points, which is 28% of the diameter of the detector. The linear speed of a scanned beam can be determined from the FWHM and the diameter of the detector aperture, ie v = diameter/FWHM or FWHM = diameter/v. In general, the exposure time per pulse, t (the FWHM), will be:

$$t = \frac{d}{v} \tag{5.8}$$

d is the diameter of the larger of the beam and the measurement aperture. Where the diameter of the beam and the measurement aperture are the same then this value is used. Note that the relevant beam diameter here is the half-power points and not the 1/e or $1/e^2$ which may be specified in the manufacturer's literature. For a Gaussian beam profile, the diameter at the 1/e point is 20% larger than the diameter at the half-power point: the $1/e^2$ point is 70% larger.

Figure 5.6 Gaussian Profile, Beam Smaller Than Detector



The MPE for the cone spinner can now be evaluated from the scan parameters. At the closest distances likely to be accessible by members of the public the laser beam diameter is probably going to be greater than the diameter of a nominal 7 mm diameter detector. Therefore, t, the exposure duration of each pass of the beam equals the beam diameter (at the 50% points) divided by the beam speed. The circumference, C, of the scan at a distance D (figure 5.3) is given by equation 5.7. The speed is given by fC, where f is the scan frequency in Hz. Therefore, t follows from:

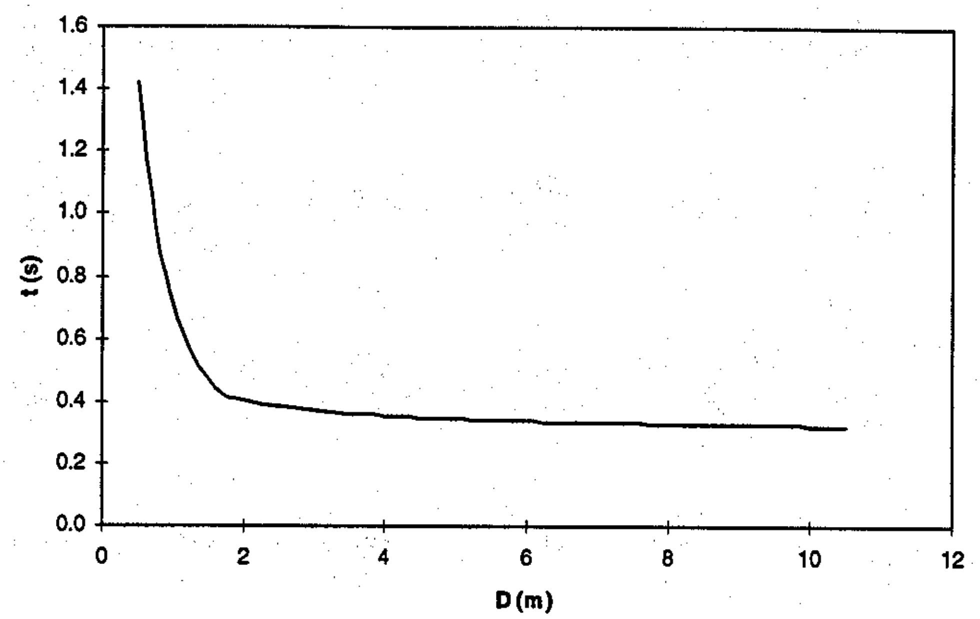
$$t = \frac{d}{fC} \qquad 5.9$$

where d is the beam diameter at distance D. Substituting for d from equation 5.3 and C from equation 5.7:

$$t = \frac{a + D\Phi}{\pi f D \sin(\Theta)} \qquad 5.10$$

A scan rate of 30 Hz should result in a solid image with no flicker. Assuming a scan angle of 3°, an initial beam diameter of 0.002 m and a beam divergence of 0.003 radians, t as a function of D can be plotted, as presented in figure 5.7. A 7 mm diameter detector is assumed, which means that 0.007 is used on the top of equation 5.10 instead of $a + D\varphi$ until $a + D\varphi = 0.007$, ie at $D = 1.67$ m in this example.

Figure 5.7 t as a Function of D



It can be seen that t is approaching a constant value. This will be within 1% of the value for D = ∞ when D = a/0.01φ. For the example above, this occurs when D = 67 m. The MPE can be determined by substituting the value for t into equation 5.1. However, the MPE can also be expressed in terms of irradiance by dividing by t. Assuming a value of 1 for C_6 the MPE for distances where d > 7 mm can be rewritten as:

$$MPE = 18\left(\frac{\pi f D \sin(\Theta)}{a + \Phi D}\right)^{0.25} \text{ W m}^{-2} \qquad 5.11$$

The maximum radiant power permitted without exceeding the MPE can be determined by multiplying the MPE by the area of the 7 mm aperture (equation 5.2):

$$P_{\max} = \frac{18\pi}{4}\left(\frac{\pi f D \sin(\Theta)}{a + \Phi D}\right)^{0.25} (0.007)^2 \text{ W} \qquad 5.12$$

This suggests that the maximum power can be increased proportional to $f^{0.25}$. However, as stated in 5.2.3, the MPE must be modified when the recipient is exposed to a train of pulses. For 18 μs ≤ t ≤ 0.25 s, the applicable MPE will generally be the reduced single pulse MPE, ie the single pulse MPE multiplied by $N^{-0.25}$. N is the number of pulses in the duration of interest, termed T. For an accidental exposure it would be appropriate to use 0.25 s. However, for audience scanning where the exposure is intentional it would be appropriate to use a longer duration. Where the actual duration of the effect is known, this could be used. However, for practical purposes the maximum exposure duration is unlikely to be greater than 10 s.

N is equal to fT. Therefore, $N^{-0.25} = 1/(fT)^{0.25}$. Substituting this into equation 5.12 gives the maximum peak power permitted into a 7 mm aperture, in a train of pulses:

$$P_{\max} = \frac{18\pi}{4}\left(\frac{\pi f D \sin(\Theta)}{fT(a+\Phi D)}\right)^{0.25}(0.007)^2 \qquad \text{W} \qquad 5.13$$

It can be seen that f now cancels out and the maximum peak power becomes independent of scan rate and proportional to $T^{-0.25}$. Therefore, considering an exposure duration of 10 s as opposed to 0.25 s only decreases the permitted power by about a factor of 2.5.

If the scan rate is increased sufficiently to bring t to below 18 μs, the relevant MPE will be the average MPE. The equivalent equation is:

$$P_{\max} = \frac{\pi}{4}\frac{18T^{-0.25}}{ft}(0.007)^2 \qquad \text{W} \qquad 5.14$$

Substituting for t from equation 5.10:

$$P_{\max} = \frac{\pi^2}{4}18T^{-0.25}\frac{(0.007)^2}{(a+\Phi D)}D\sin(\Theta) \qquad \text{W} \qquad 5.15$$

This again shows that the maximum peak power is independent of the scan speed. However, a check should also be made to ensure that the reduced single pulse MPE is not more restrictive. These results are extremely significant. A major argument used by laser display companies is that the risk of eye damage is decreased by increasing the scan speed with any control measure acting before the scan slowed below some (unspecified) value. This argument can only be used if increasing the scan speed does not increase N. A spreadsheet to demonstrate how the scan speed can be used by stalling the scanner for a period of time after each scan and reduce the exposure to below the MPE has been developed (Walker 1997). However, this spreadsheet uses the assumption that the beam can be scanned faster than commercially available scanners will permit, and the beam is assumed to be parked and blanked for a significant proportion of the scan frame. Such effects are unlikely to be visually acceptable, even if the scanner technology did exist.

5.5.4 Measurement of Scanned Beams

As identified in Chapter 3, it was normally difficult to obtain information on the laser beam characteristics. The manufacturer's data on the radiant power and the beam divergence for a laser may be altered by the optical systems employed to manipulate the beam. In order to theoretically assess exposure to beams, as described in the previous section with a simple cone spinner, it is necessary to know the scan rate, beam divergence, scan angle, initial beam diameter and the radiant power of the laser.

The use of proprietary laser power meters to assess scanned beams can lead to significant errors. As shown in 5.2.3, it is important to know the energy per pulse or the peak power. Commercial energy meters are not generally sensitive enough to detect the energy in a 5 W beam scanned across a 7 mm aperture in 10 - 100 μs. Depending on the design of a power meter, it may indicate true average power or, for modern digital sampling detectors, widely varying powers. This is due to the resultant signals at the sampling times being either during an actual exposure of the detector or during the period between exposures. Power meters such as the Coherent Fieldmaster with a silicon LM2 head present an erratic answer which, to the skilled user, indicates that the result is not reliable.

In order to evaluate scanned beams it was necessary to use a basic design of detector which consisted of a silicon photodiode, transimpedence amplifier and an oscilloscope. Two detectors were principally used for this research: a Centronics 50 mm^2 diameter photodiode with a 7 mm diameter circular aperture mask, for direct comparison with the MPE and a Hamamatsu S2858-01 detector with integral transimpedance amplifier for beam profiling. This technique proved a very effective alternative to commercial beam profiling equipment which scans across the beam.

Equation 5.10 shows that the time of scan across a 7 mm aperture is a function of many of the required parameters for input to the comparison with the MPE. If the scan time measurement can be made at a number of distances from the effective source it is possible to determine these parameters.

A nominal 1.3 mW helium-neon laser emitting a green beam (543.5) (Gre-Ne) was input to a Maplin scanner (cone spinner) driven from a custom power supply. One of the two motors in the scanning unit was driven and the laser beam scanned until the resultant image formed a solid circle on a screen. The Centronic detector was used to measure the scan time, t, as a function of distance from the scanning mirror.

5.5.5 Results

The detector voltage as a function of time is plotted in figure 5.8 for distances of 2.5 m to 7 m in 0.5 m intervals; figure 5.9 for 7 m to 19 m in 1 m intervals and figure 5.10 for 15 m to 19 m.

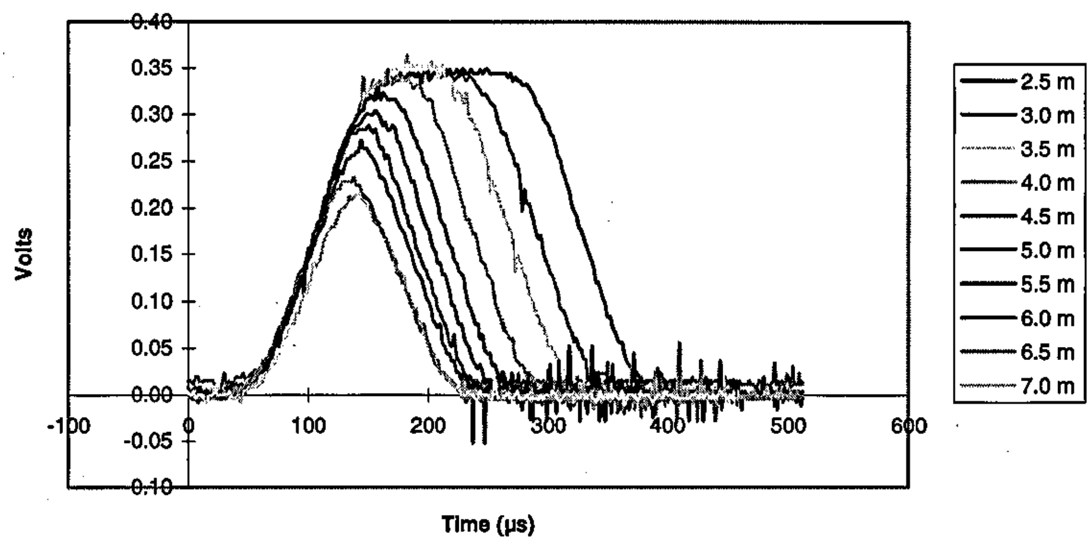


Figure 5.8 Maplin Scanner Gre-Ne Laser 2.5 to 7 m

It can clearly be seen in figure 5.8 that the laser beam was smaller than the detector diameter at distances from 2.5 to 4 m since the detector output is constant for a period of time. This plateau is reduced as the distance increases and the beam diameter increases. At about 4.5 m the beam diameter is approximately the same size as the detector aperture. As the distance is increased beyond 4.5 m the amplitude of the detector voltage decreases as a reducing proportion of the beam enters the detector. For comparison with the Standard (BSI 1994), the beam diameter is defined at the 1/e point, ie the largest aperture which collects 63% of the beam. The maximum voltage recorded when the total beam was collected was 0.35 V. Therefore, 63% of the beam will be collected when the peak voltage is 0.22 V. This represents a distance of between 6 and 7 m. The specification for the Gre-Ne laser gives an initial beam diameter of 1 mm and a beam divergence of 1 milliradian. From this, the beam diameter would be 7 mm at 6 m. This is consistent with the observed value.

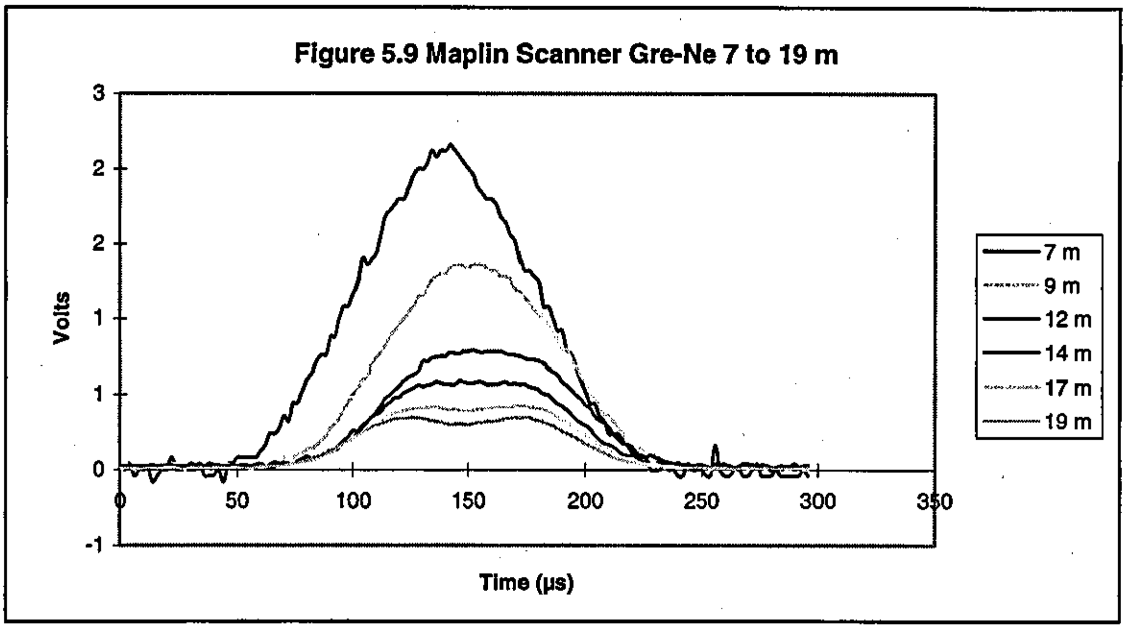


Figure 5.9 Maplin Scanner Gre-Ne 7 to 19 m

The gain of the detector was increased by a factor of about 10 when the distance was increased to 8 m. The 7 m response is multiplied by 10 and replotted in figure 5.9. It can be seen on this figure that the amplitude of the pulse seen by the detector continues to decrease with increasing distance as the detector samples a smaller segment of the beam as it scans past. It is interesting that some structure starts to appear in the pulse shape at distances from 17 m. Therefore, the pulses are replotted in figure 5.10. At 19 m, the theoretical beam diameter is 20 mm, or about three times the diameter of the detector. The Gre-Ne was understood to have a TEM$_{00}$ mode structure and therefore should have been producing a gaussian beam profile. To confirm this, a proprietary beam profiling device using a CCD camera connected to a laptop computer was used to analyse the beam. This device focussed the incoming beam onto a 256 x 256 CCD array and produced an output from each element from 0 to 255. This confirmed that the Gre-Ne was operating in TEM$_{11}$ mode and that the pulse shape seen by the detector as the beam scanned past was a section through this TEM$_{11}$ profile.

Figure 5.10 Maplin Scanner Gre-Ne 15 to 19 m

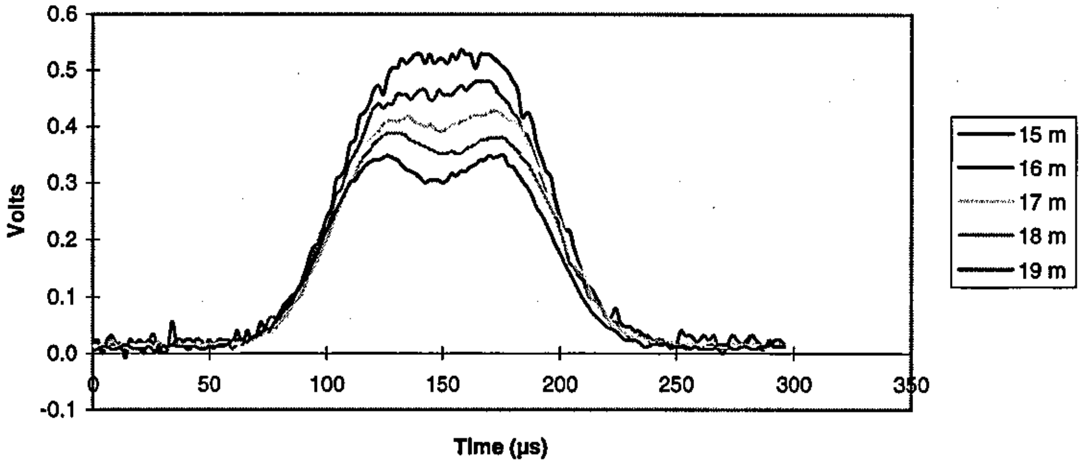
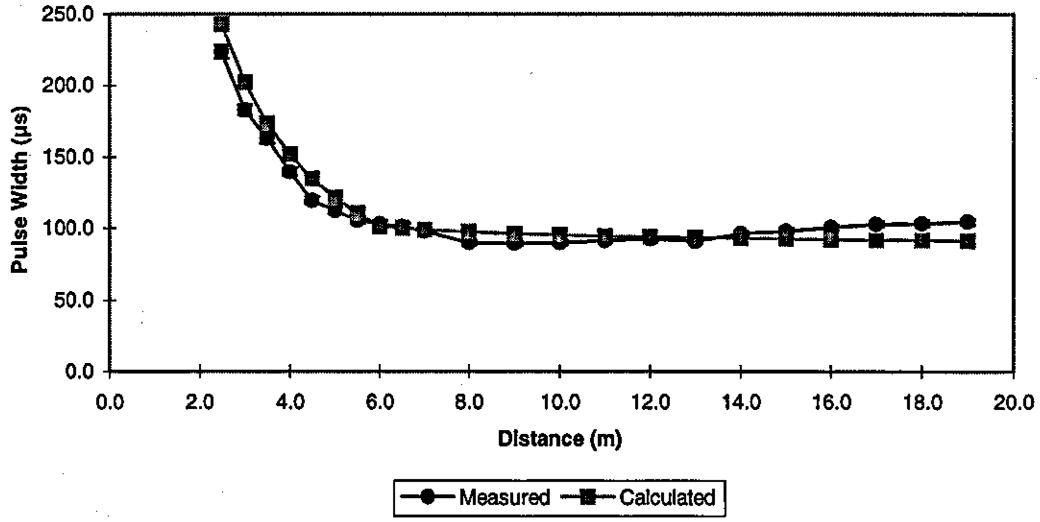


Figure 5.11 Comparison of Measured and Calculated Pulse Widths



The pulse width as a function of distance is plotted in figure 5.11. It was possible to determine the scan rate at each distance by increasing the delay on the oscilloscope trigger until the next pulse was seen. The scan rate was determined by the inverse of the time between peaks. During the course of the 22 measurements the mean scan rate was 37.6 Hz (standard deviation 0.4 Hz). Using this value for f, a beam divergence of 1 milliradian, an initial beam diameter of 1 mm and a full scan angle, ϑ, of 5.6° (determined from measuring the diameter of the scan pattern as a function of distance, D) it was possible to calculate the pulse width using equation 5.10 and these values are also plotted on figure 5.11.

It is of note that the pulse width reaches a constant value once the beam diameter is greater than the diameter of the detector. Essentially, the beam forms a constant proportion of the scanned circle as a function of distance. The minor deviation between the measured and calculated values at increasing distance is considered to be due to the increasing importance of the tails of the beam profile as smaller percentage segments of the total beam are scanned across the detector.

5.5.6 Discussion

Since a cone scan is one of the most popular audience scanning effects, the results from this analysis are extremely significant. A typical laser installation will be using a laser with a radiant power of 4 W, a beam divergence of 3 milliradians, and an initial beam diameter of 2 mm. Assuming a Gaussian beam profile, it is possible to calculate the NOHD for a cone for a given scan angle. As has already been shown, the pulse duration reaches a constant value with increasing distance, but the proportion of the beam entering the nominal 7 mm diameter aperture decreases because of the beam divergence. One way of reducing the NOHD, of course, is to increase the beam divergence. The closest point of access for the audience should be greater than the NOHD. Therefore a balance should be struck between the closest reasonable point of access and the beam divergence.

Table 5.3 NOHD (m) for a Cone Scan as a function of Divergence and Scan Angle

Divergence (milliradians)→ Scan Angle (degrees)↓	1	2	3	4	5	10	20
1	248.6	135.6	95.1	73.9	60.8	33.2	18.1
2	228.0	124.3	87.2	67.8	55.8	30.4	16.6
3	216.8	118.2	82.9	64.4	53.0	28.9	15.8
4	209.1	114.0	80.0	62.2	51.1	27.9	15.2
5	203.4	110.9	77.8	60.5	49.7	27.1	14.8
6	198.8	108.4	76.0	59.1	48.6	26.5	14.5
7	195.0	106.3	74.6	58.0	47.7	26.0	14.2
8	191.8	104.6	73.3	57.0	46.9	25.6	13.9
9	189.0	103.1	72.3	56.2	46.2	25.2	13.7
10	186.6	101.7	71.3	55.5	45.6	24.9	13.6

The influence of the scan angle and the beam divergence on the NOHD for a 4 W cw laser are presented in table 5.3. This has been calculated by setting equation 5.11 as equal to the irradiance for a 4 W beam and solving for D equals the NOHD with the approximation that the initial beam diameter is zero (equation 5.16):

$$NOHD = \sqrt{\frac{4P_o}{18\pi\Phi^2}\left(\frac{T\Phi}{2\pi\sin(\Theta)}\right)^{0.25}} \quad \text{m} \qquad 5.16$$

It can be seen from table 5.3 that doubling the divergence reduces the NOHD by about 50%. However, doubling the scan angle only reduces the NOHD by about 8%. This demonstrates the effectiveness of increasing the divergence for beams which may enter the audience area.

These results show that it is possible to determine the exposure condition when the laser beam is scanning at a constant speed. However, scanned effects are generally not produced using spinning mirrors, they are produced by pairs of galvanometers under programme control. The images will range in complexity from circles and straight lines through to sophisticated graphical representations. An introduction to the format of the data and the representations of the images is presented in Appendix A.

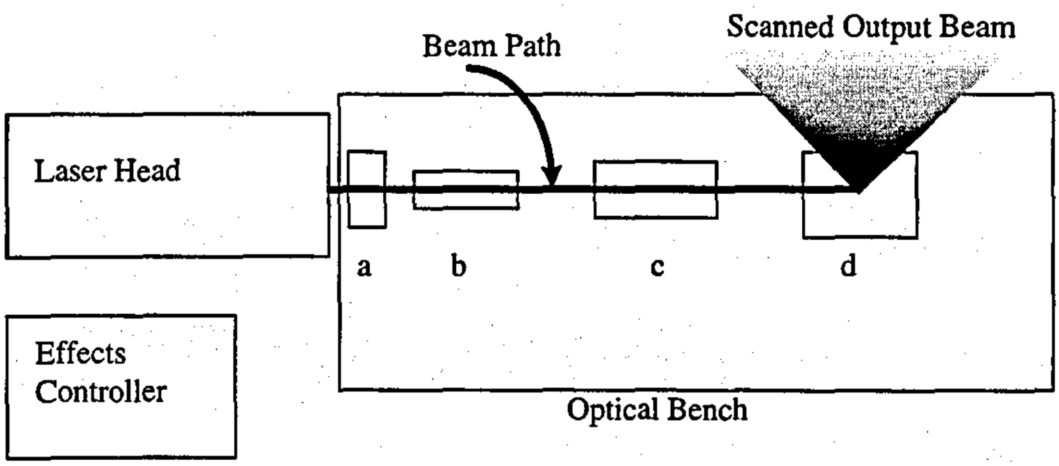
5.6 Measurements on Proprietary Scanning System

A proprietary laser display system was loaned by a laser display company and measurements made under laboratory conditions to determine the characteristics of scanned images. A schematic of the laser and the primary optical system is presented in figure 5.12.

5.6.1 Measurement Method

Measurements were undertaken using the 7 mm diameter photodiode, transimpedence amplifier and oscilloscope arrangement used in 5.5.1. In addition, a custom thermopile detector was used to determine average power (Corder 1997).

Figure 5.12 Proprietary Laser Display System



Key: a - height adjusting periscope; b - colour selectors;
c - blanking telescope; d - scanning galvanometer pair

An air-cooled argon ion laser was used as the source. The radiant power of the static beam was 6.48 mW, measured using a calibrated Coherent Fieldmaster with an LM-2 detector. The power output from the laser was 7.90 mW, representing a loss of 18% of the input beam through the optical system. The beam diameter was 5 mm at the measurement position (3.95 m from the scanner to the detectors). The irradiance was calculated by averaging the radiant power over a 7 mm limiting aperture and was 168.4 W m^{-2}. Measurement of the radiant power requires the drive signal to the blanking telescope to be disconnected or the mirror moved out of the beam path. Many patterns generated by the control system include an element of blanking. As described earlier, measurements using a sampling power meter will be in error for beams which do not have a constant irradiance with time.

The assessed scan pattern was a cone, which was collapsed, ie x was fixed, to produce a flat (or line) scan in the vertical plane. Measurements were made at 11 positions along the scan using the photodiode to determine the duration of each 'pulse' as the laser beam scanned past the detector and the number of pulses per second; and the thermopile detector to determine the average irradiance. The measured pulse duration per scan from the photodiode detector is presented in table 5.4. The thermopile detector results are presented in table 5.5. Examples of the output voltage as a function of time from the photodiode are presented in figure 5.13 at the end of the scan (position 1 - left end of scan pattern in figure A.3) and figure 5.14 for the positions away from the end of the scan. It is significant that a person located at either end of the scan would receive half the number of pulses as a person at any other point along the scan. At the mid-position, the spacing between the pulses should be equal.

5.6.2 Results

The scan refresh rate was determined from the time between pulses at the end of the scan and was found to be 120 Hz. Therefore, at the ends of the scan, a person would be exposed 120 times per second and elsewhere in the scan at 240 times per second, in the absence of any aversion response. Assuming the natural aversion response and an accidental exposure, then it would be reasonable to assume an exposure duration of 0.25 s. The number of pulses received, N, would then be the above figures divided by 4.

Table 5.4 Measured exposure duration per scan from photodiode detector

Position	t (μs)	N for 0.25 s exposure	Reduced single pulse MPE	Maximum radiant power into 7 mm to not exceed MPE (mW)
1 (end)	366	30	55.6	2.14
2	78.6	60	68.7	2.64
3	50.0	60	76.9	2.96
4	36.8	60	83.0	3.20
5	30.0	60	87.4	3.36
6	26.1	60	90.5	3.48
7	26.2	60	90.4	3.48
8	26.4	60	90.2	3.47
9	24.9	60	91.6	3.52
10	24.7	60	91.7	3.53
11	25.2	60	91.3	3.51
Measured irradiance and radiant power through 7 mm aperture			168.4	6.48

Table 5.5 Thermopile detector measurements

Position	Measured average irradiance	Measured irradiance divided by $MPE_{average}$
1	21.5	0.85
2	5.63	0.22
3	3.60	0.14
4	2.70	0.11
5	2.18	0.09
6	1.90	0.07
7	1.83	0.07
8	1.83	0.07
9	1.63	0.06
10	1.50	0.06
11	1.53	0.06

5.6.3 Discussion

The results in table 5.4 demonstrate that the maximum power into a 7 mm aperture is of the order of a few mW. Even at 6.48 mW, the MPE will be exceeded at any position along the scan pattern. This can be compared with the MPE for the static beam, which would be 1 mW for a 0.25 s accidental exposure. However, if the average power is measured and compared with the average MPE, as in table 5.5, then it implies that the scan pattern is safe and also that the 'safety margin' between the end of the scan pattern and the middle (positions 1 and 10) increases by a factor of 14.

Figure 5.13 Photodiode Output at Position 1 of Flat Scan

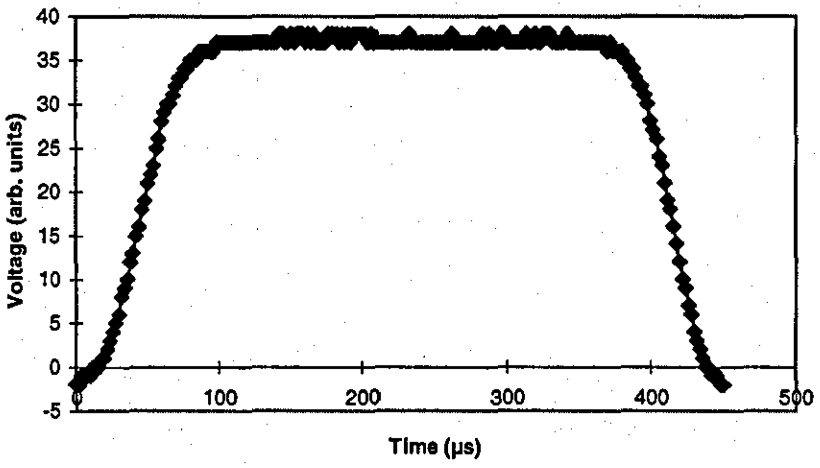
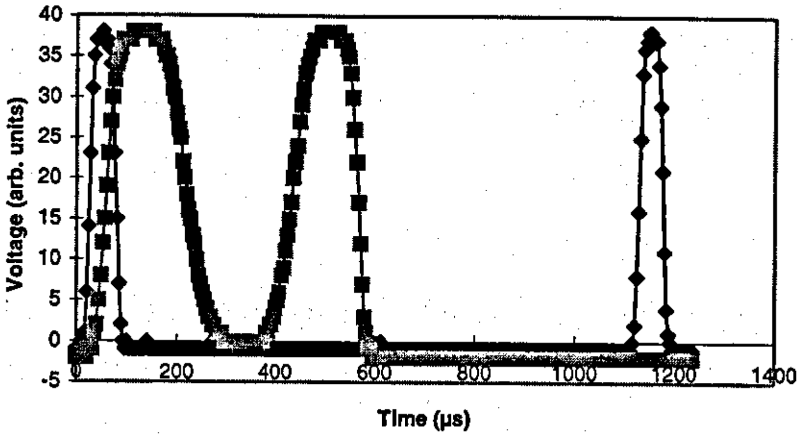


Figure 5.14 Photodiode Output Showing Twin Passes of Beam



The twin pulses close to position 1 in figure 5.14 clearly show the beam slowing down as it crosses the detector the first time and then accelerating away from a stationary position during the second pass. The times between 20 and 80% of peak value are 35 μs rise, 68 μs fall, for the first peak and 58 μs rise and 28 μs fall for the second peak. In comparison, the two pulses at position 3 are symmetrical.

An inspection of the photodiode output as a function of time on the oscilloscope presents the opportunity to understand the nature of the scanned pattern. During the study of the time between successive pulses the plot presented in figure 5.15 was obtained.

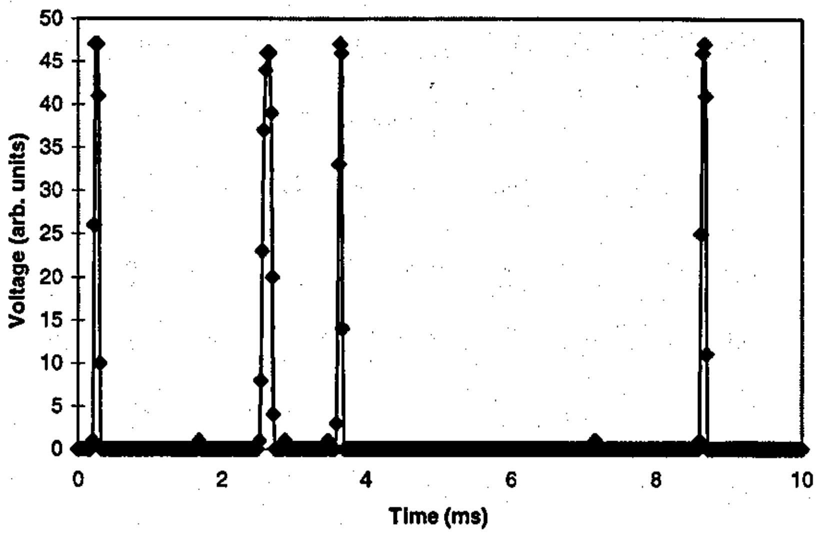


Figure 5.15 Photodiode Output. Position with 3 Pulses per Cycle

Figure 5.15 shows three peaks per scan cycle. The fourth peak occurs about 8.3 ms after the first pulse representing the 120 Hz refresh rate. It was initially thought that the three peaks were an artefact of the oscilloscope but further inspection of the scan pattern on the screen showed a small section of the pattern which was brighter to the eye. A plot of the x,y,z data to the driver boards of the scanners and z-blanking showed that there was an overlap of the scan pattern. It appears that the scan pattern had been digitised by hand (as a circle) and the engineer had put in a small overlap to ensure that there was no gap in the circular pattern. The scan was then blanked to allow the scanners to return to the start position and recommence the scan.

The respective times of exposure to the first three pulses (full width, half maximum) in figure 5.15 were approximately 64, 140 and 60 μs. There is no clear guidance on how to assess multiple pulses of different durations. However, it would be reasonable to assume that the MPE would be somewhere between that applicable for three pulses of 60 μs duration per cycle and three of 140 μs duration. In both cases, N, for a 0.25 s accidental exposure, will be 90. From section 5.2.3, the reduced single pulse MPE will be 66.39 and 53.73 W m^{-2} for the 60 and 140 μs pulses, respectively. Therefore, the maximum power into a 7 mm aperture is between 2.61 and 2.12 mW. By comparison with table 5.4 it can be seen that the small overlap region may present a greater hazard than any other part of the scan pattern.

This exercise demonstrates the importance of using the correct measurement instrument to undertake the measurements and the importance of applying the correct MPE (Corder, O'Hagan and Tyrer 1997, O'Hagan, Corder and Tyrer 1998). From position 11 in table 5.5, it can be seen that the average irradiance would suggest a safety margin of about a factor of 16. However, the same position in table 5.4 shows that the MPE was actually exceeded by a factor of 2. Therefore, the error in this one position is about a factor of 32.

Most scanned laser effects will be more complex than flat or cone scans. They may also move and change size with time. Indeed, many scanned effects will be animations. Although most complex graphical images will be projected onto screens away from the audience, the patterns used to scan across the audience as beam effects, are generated in an identical manner. A number of effects from a proprietary laser display system were assessed at a number of positions in the scan pattern to determine the maximum radiant power into a 7 mm aperture to keep below the MPE.

5.7 Zig-Zag Pattern

The x-y data for a zig-zag pattern is presented in figure 5.16. If the value of y is kept constant then the scanned pattern will appear as a number of fingers of light in space. Figure 5.17 shows the scan drive signals as a function of time. The inertia of the galvanometers will mean that the actual movement of the laser beam will not precisely follow the drive instructions, but it is still likely that the beam will reduce speed, if not stop, at the horizontal positions on the plot in figure 5.17.

5.7.1 Measurements

Using the photodiode detector, measurements were made along the scan pattern to determine the exposure duration of a 7 mm aperture. The beam diameter at the detector position was 5 mm, the scan width was 0.72 m and the distance between the visibly brighter regions of the pattern projected on to a screen was about 53 mm.

5.7.2 Results

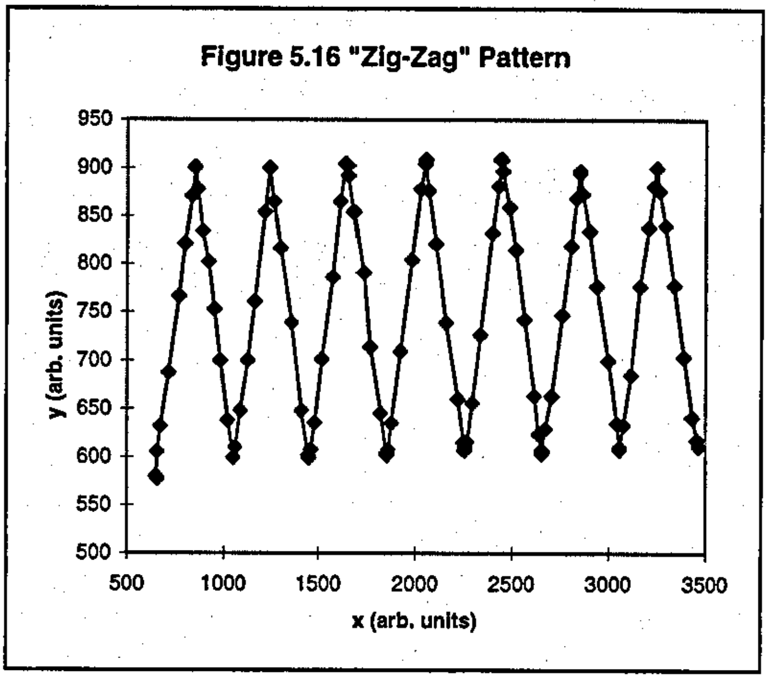


Figure 5.16 "Zig-Zag" Pattern

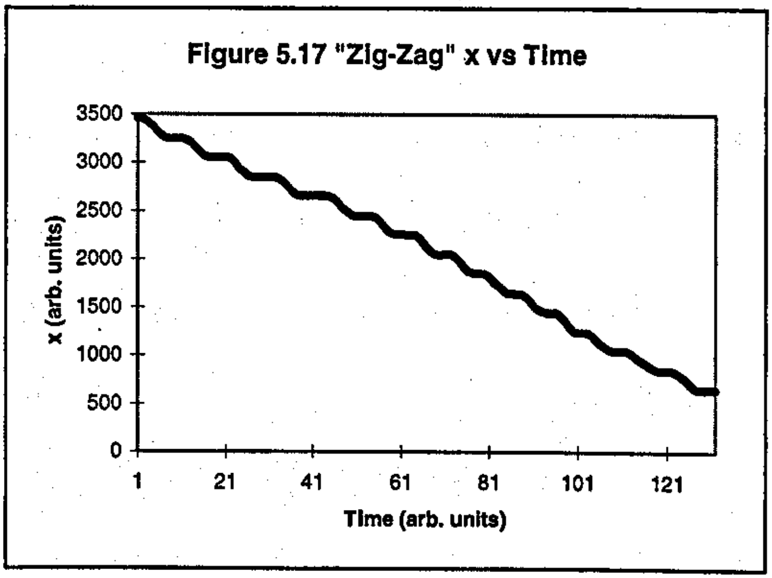
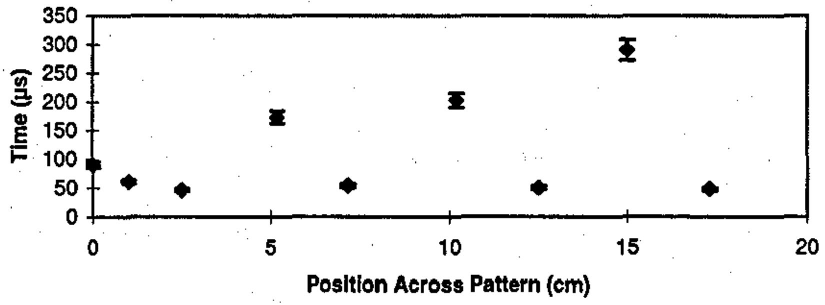


Figure 5.17 "Zig-Zag" x vs Time

The full width half maximum values for the measured pulsed durations are presented in figure 5.18. There appears to be a trend of increasing pulse duration at the dwell points but the durations at the intermediate points (approximately 40 μs) suggest that the speed at these points is relatively constant across the width of the scan pattern. The measured exposure durations can be used to determine maximum irradiances at these positions to comply with the MPE. Using the minimum (45.8 μs) and the maximum (289.8 μs) this gives a maximum irradiance of 219 and 138 Wm^{-2}, respectively, for a single pass of the beam. Assuming a scan rate of 100 Hz, and an aversion response time of 0.25 s, the irradiances reduce to 97.9 and 61.7 Wm^{-2}. These represent 3.9 and 2.4 mW into a 7 mm aperture.

Figure 5.18 Measured Pulse Widths for Zig-Zag



5.8 Complex Graphical Pattern

The zig-zag pattern is relatively straightforward - each position on the scan pattern is visited by the beam in a single pass across. Many images are complex and created by re-visiting the same position a number of times. Such images may also be animated. The graphical image in figure 5.19 is a single frame from the library of a commercial laser display system. The figure (Cuddles) performs an Egyptian dance. Some parts of the image are blanked so that the detail around the eye, for example, is clearer than implied from the x-y data alone.

5.8.1 Measurements

Measurements were made at a number of positions on the single frame (1 to 7 marked on figure 5.19) to determine the irradiance as a function of time, averaged over a 7 mm aperture. The laser beam diameter (as determined by eye) was 4 mm at the measurement position. The graphical image was 0.35 m from finger tip to finger tip and 0.46 m from the top of the head to the base of the feet.

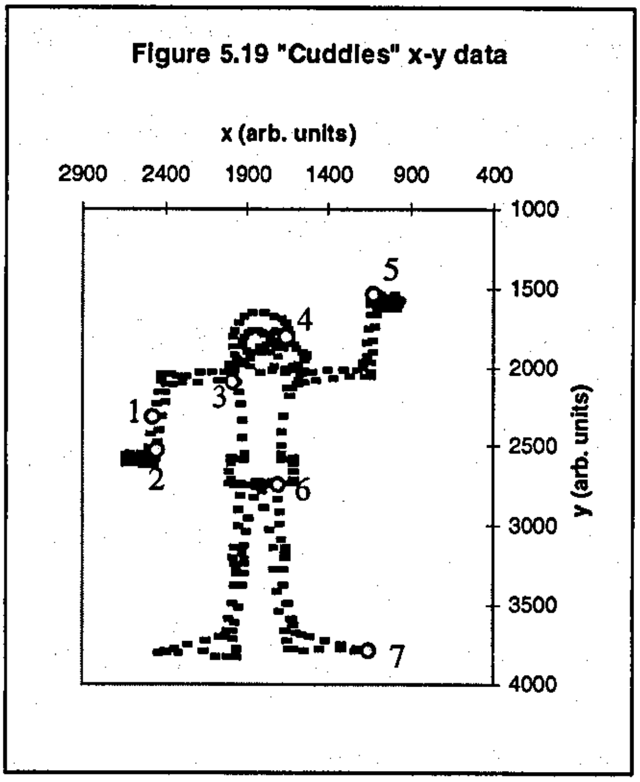


Figure 5.19 "Cuddles" x-y data

5.8.2 Results

The detector output as a function of time is presented in figures 5.20 to 5.26 for positions 1 to 7, respectively.

Figure 5.20 Cuddles Position 1

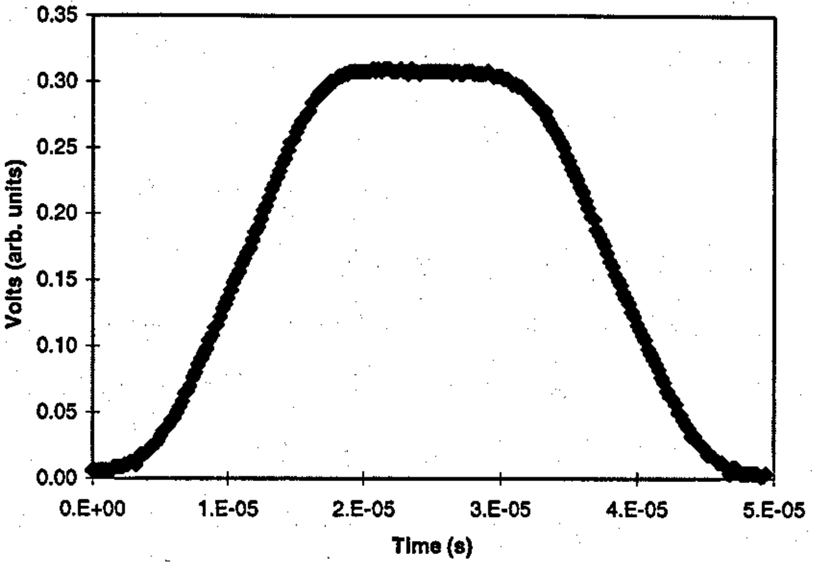


Figure 5.21 Cuddles Position 2

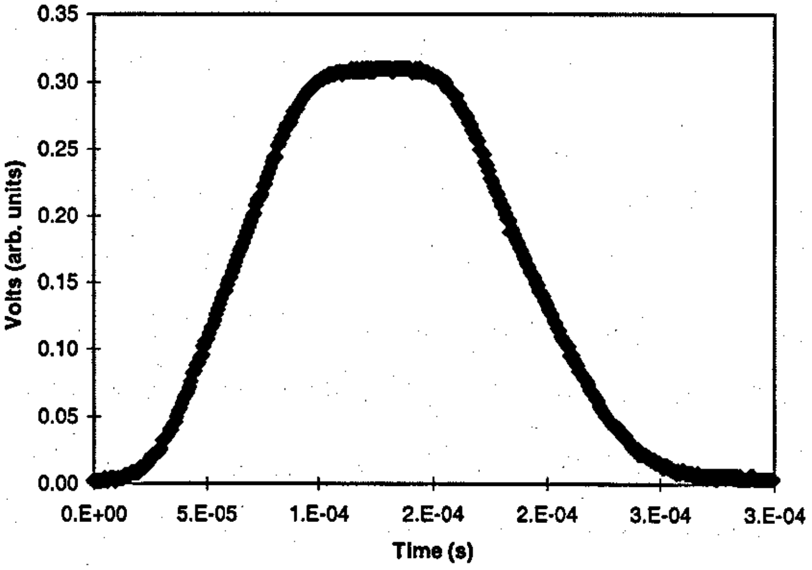


Figure 5.22 Cuddles Position 3

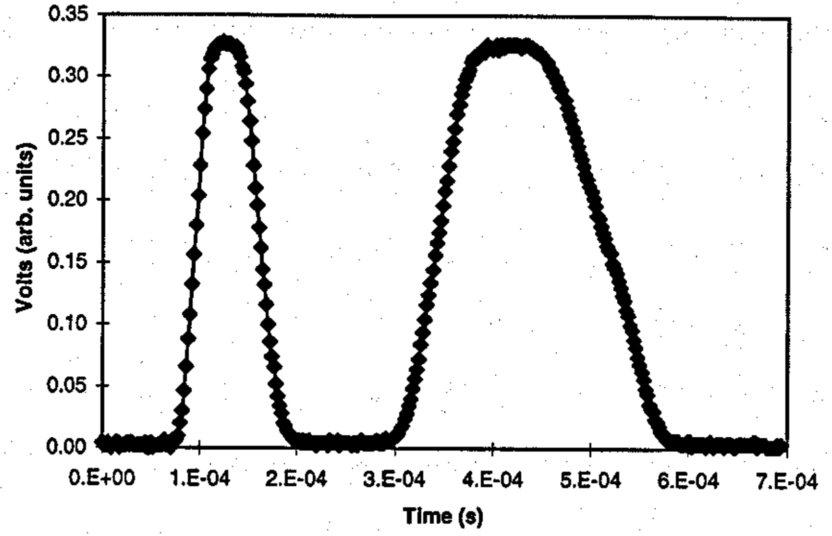
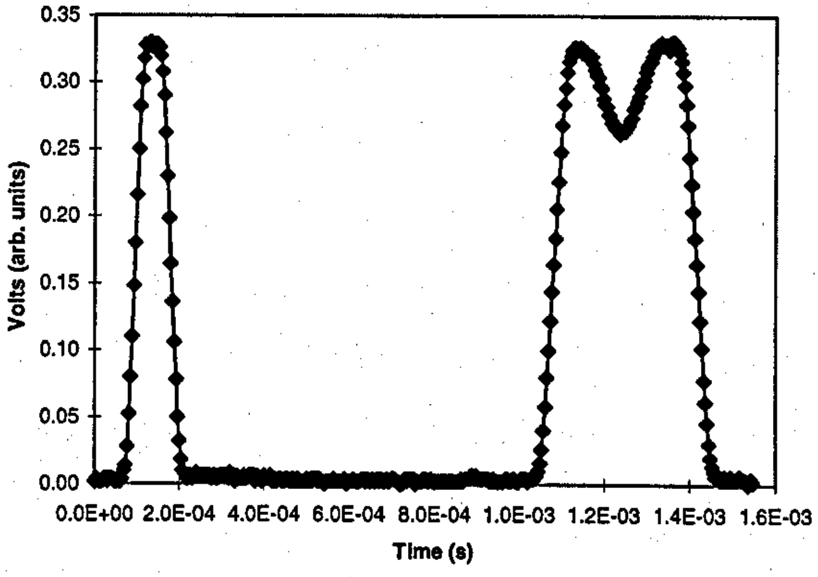


Figure 5.23 Cuddles Position 4



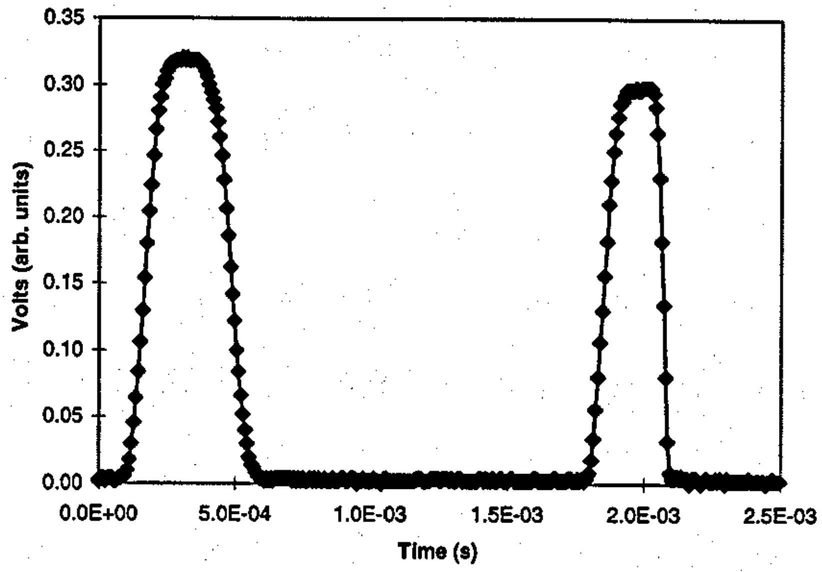


Figure 5.24 Cuddles Position 5

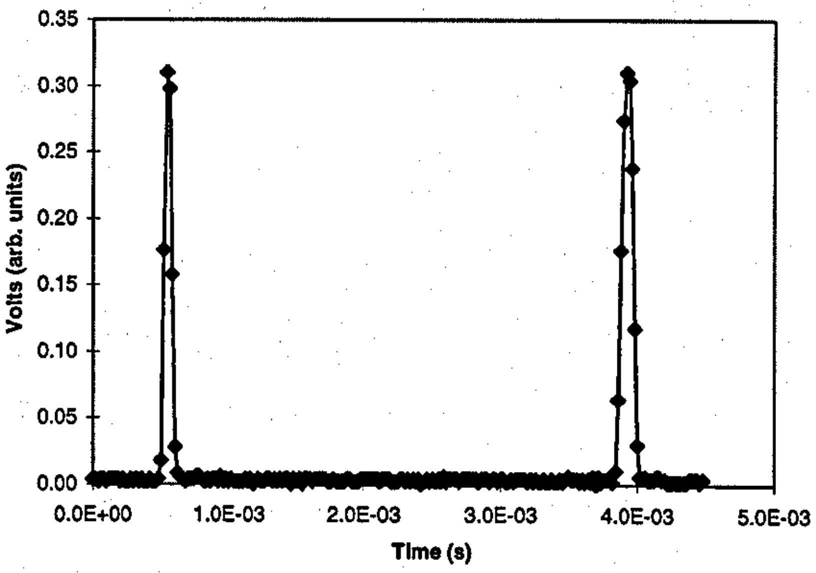


Figure 5.25 Cuddles Position 6

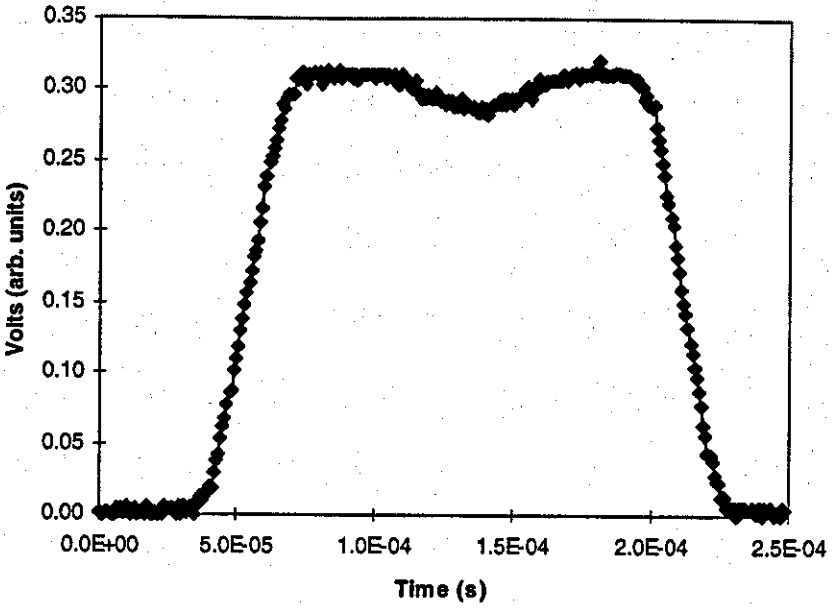


Figure 5.26 Cuddles Position 7

Table 5.6 Analysis of Cuddles Scan Pattern

Position	No. of Pulses per Frame	Pulse Width (µs)	MPE_{single} (W m^{-2})	P_{single} (mW)	MPE_{train} (W m^{-2})	P_{train} (mW)
1. Straight of arm	1 (33 Hz)	28	247	9.5	146	5.6
2. Right hand	1 (33 Hz)	133	167	6.4	98	3.8
3. Right armpit	2 (33 Hz)	67	198	7.6	117	4.5
		174	156	6.0	92	3.5
If both pulses same	(66 Hz)	174	156	6.0	77	2.9
If pulses combined	(33 Hz)	241	144	5.5	85	3.2
4. Eye	2 (33 Hz)	86	186	7.1	110	4.2
		340	132	5.1	78	3.0
If both pulses same	(66 Hz)	340	132	5.1	65	2.5
If pulses combined	(33 Hz)	426	125	4.8	73	2.8
5. Left hand	2 (33 Hz)	310	135	5.2	80	3.0
		220	147	5.6	87	3.3
If both pulses same	(66 Hz)	310	135	5.2	67	2.5
If pulses combined	(33 Hz)	530	118	4.5	69	2.6
6. Top of leg	2 (33 Hz)	59	205	7.9	121	4.6
		99	180	6.9	106	4.0
If both pulses same	(66 Hz)	99	180	6.9	89	3.4
If pulses combined	(33 Hz)	158	160	6.1	94	3.6
7. Left toe	1 (33 Hz)	159	160	6.1	94	3.6

5.8.3 Discussion

The pulse data was analysed for each position. The pulse width was taken as the full width half maximum for each pulse. Where the pulse was not resolved at the half maximum it was treated as a single pulse. The time to the next pulse, or pulse group, as appropriate was determined to ensure that all of the pulses in the single scan of the image had been identified. The refresh rate for the scan was 33 Hz.

As stated in 5.5.2, there is no guidance within the British or International Standard on how to analyse groups of pulses where the time interval between the pulses is not a constant value. Therefore, for positions 3 to 6, which all were visited more than once during a scan cycle, the MPE was calculated using the following options: each pulse was analysed independent of the other pulse; both pulses were assumed to have the pulse width of the longer duration pulse; and it was assumed that there was only one pulse per scan cycle of duration equal to the sum of the duration of the individual pulses. This is presented in table 5.6. The final column of table 5.6 gives the maximum power averaged over a 7 mm aperture in order not to exceed the MPE. The range of pulse widths is from 28 to 530 μs, but the power limit only ranges from 2.5 to 5.6 mW. This result supports the argument presented with the simple scan pattern (table 5.3) that the power averaged over 7 mm diameter apertures for compliance with the MPE must be much lower than the radiant powers of the lasers typically used in the entertainment industry.

5.9 Conclusions

Measurement of the characteristics of the laser beams used in laser displays is important for quantifying the laser radiation hazard. This is required as input to the risk assessment. Generally, if the irradiance is less than the maximum permissible exposure then the risk of injury is low. As the irradiance is increased above the MPE then the risk of injury increases. This takes no account of other sub-threshold effects such as dazzle, distraction and after-images. For a seated audience such effects may not be significant. However, if the laser beams extend beyond the confines of the venue then such effects may be important, for example pilots and drivers of motor vehicles may be at particular risk.

Many lasers used in the entertainment industry are Class 3B or Class 4 and the radiant powers may be 20 W or more. Lasers with radiant powers of the order of 5 W are routinely used for audience scanning. It is important to appreciate that, with a scanned laser beam, the peak power is incident on the target for a period of time. For many years, assessments of audience scanning effects have been carried out using laser power meters which, at best, give an indication of average power and may not respond at all, thus giving the impression that the exposure condition is well below the MPE. It is therefore extremely important for either scanned effects to be analysed properly, or for worst case assumptions to be made. The latter includes measurement of the stationary beams at the closest audience locations.

It is possible to predict the irradiance conditions for simple scanned patterns, such as cones. The analysis presented in this chapter was supported by measurements of an actual scan pattern to demonstrate that the speed of the scan had no effect on the MPE. This result is extremely significant. Many laser display companies are under the impression that their scan patterns are safe because they scan at speed. However, many of these companies are not able to quantify their scan parameters and generally do not have laser irradiance/power measuring equipment which will respond to the scanned beams. The results from the thermopile detector demonstrate how the use of an average power meter can be misleading. Average power is not the appropriate quantity for comparison with the MPE.

Measurements of the pulse duration, ie the exposure of a theoretical 7 mm diameter 'eye' was used to determine the applicable MPE, generally the reduced single pulse MPE or the MPE_{train}, and the maximum radiant power permitted through this aperture was determined from the pulse duration and number per scan, or frame. In all cases this radiant power was less than 10 mW. Where the scan rate was low such that the pulse width reached 0.5 ms, the maximum radiant power was 2.5 mW. This should be compared with the MPE for a static beam, which would be 1 mW for a single accidental exposure assuming the 0.25 s aversion response.

The conclusion is that the assessment of scanned beams can be greatly simplified by measuring the power of a static beam through a 7 mm diameter aperture. If this is 1 mW or less then the MPE will not be exceeded at any position in the scan pattern. This can probably be increased to 2 mW for most scan patterns (see table 5.4) but any further increase will require significant effort to analyse each scan pattern, including any failure modes.

Limiting audience scanning beams to 2 mW into a 7 mm aperture can be achieved by using a low power laser such that the radiant power of the laser is less than 2 mW. This will limit the effectiveness of the beam effect where audience scanning is not required. Therefore a more effective control measure will be to increase divergence, and therefore, the diameter of a higher power laser beam such that the power entering the 7 mm diameter aperture is less than 2 mW. This could be achieved by the use of a lens. Another advantage of this approach is that the lens could be mounted at an aperture used for audience scanning. Other apertures from the optical system could be used for other effects, but these would need to be blanked to ensure that the beam could not stray into occupied areas. It would also be possible to combine two apertures to produce a scan pattern. For example, a cone scan could be generated by the top section projected overhead as a well collimated beam through one aperture whilst the lower section, which was projected into the audience passes through a different aperture, close to the first, but incorporating a lens.

Diffractive elements are becoming widely available which generate complex images. These allow laser effects to be produced, such as flat patterns, cones and cartoon characters without scanning the laser beam. Such elements could be rotated and selected, for example by mounting into a rotating cassette. Since the beam is not scanned, the peak radiant power is much lower and is truly averaged over the pattern. Such effects are currently limited since they need to take account of the size of the venue, etc. However, devices are currently being developed which will allow a diffractive element to be active and programmable to produce the desired effect.

In summary:

1. Audience scanning is currently carried out without adequate quantification of the hazard.
2. Analysis of beam effects is complicated for anything other than simple scan patterns.
3. Increasing the speed of a scan pattern does not make it safer.
4. Measurements of scan patterns are not made with appropriate instrumentation. Such

measurements need to determine the duration of exposure for each scan pass the eye, the peak irradiance averaged over the 7 mm diameter eye, and the number of exposures within a suitable time frame, 0.25 s, say.

5. The analysis of complex scan patterns demonstrates that the maximum power into a 7 mm aperture is less than a factor of ten above the MPE for a static beam, and often only a factor of two greater.
6. The analysis can be simplified by assessing static beams only.

These conclusions are significant for putting the laser radiation hazard into context with other hazards which may be present at a laser display.

6. Laser Hazard Assessment Model

6.1 Introduction

The previous Chapters have outlined the problem for both enforcing officers and those involved in the laser entertainment industry. Although there are many aspects to consider it is important to appreciate that most are common to both groups of people. The aim was to develop a methodology to enable a suitable and sufficient assessment of the risks associated with the laser display to be carried out. Before the risks can be assessed it is necessary to identify the hazards. One of the main issues has been consistency of approach to assessing the laser safety issues. The laser companies do not consider safety a big issue. They are generally working on tight financial margins and most have not experienced major injuries.

The survey of the enforcing officers and feedback from the training provided suggested that few, if any, of them were in a position to assess the safety of laser displays. Where training has been provided the skills are not developed due to the small number of assessments which may be undertaken by a particular officer. A methodology is needed to ensure that the enforcing officers can work through the key elements of the safety issues. It may still be that they will not be able to carry out complete assessments but at least they should be in a position to appreciate where further assistance is required and where they can call on their existing expertise to assess much of the installation.

It is also ideal to develop a methodology which is helpful to the laser companies. Whilst it is easy to conclude that they do not care about the safety issues, it may be that they have not been forced to think them through. A successful methodology may also provide commercial benefits to laser companies. Demonstrating professional competence, which includes assessing the safety issues, is becoming increasingly important in the entertainment industry. This information will be useful for venue managers and promoters as well as to the enforcing officer.

This Chapter describes the development of a model which can be used by all parties, and which covers all applications of lasers in the entertainment industry. The methodology should provide a structured approach to identifying hazards which can then be input to a risk assessment. It will be seen that the development of the formal guidelines, both national and international should have provided ideal opportunities for the introduction of a suitable risk assessment methodology. However, this was not to be the case. The involvement and influence of both the International Laser Display Association and the Entertainment Laser Association are described.

6.2 Development of Initial Assessment Checklist

One of the main comments from local authority Environmental Health Officers concerning laser displays is that they would prefer to work to a prescriptive hazard identification checklist. To a certain extent HSE PM19 (HSE 1980) provided this. However, the document did not go far enough. The aim through the current research has been to produce a methodology which was useful to the enforcing officer but also had benefits for the venue management and the laser company. The latter should see an improvement in efficiency and management of laser displays. The approach would also go some way to remove inconsistencies between enforcing officers which has been a justifiable criticism made by many laser companies.

A generic model for laser hazard assessment has been developed by Tyrer et al (1994). This model treats the laser, beam delivery and workpiece as separate parts of any laser product. However, for the entertainment and display industry this model can be developed further into a checklist. One of the benefits of this approach is to ensure that any hazard assessment is carried out in an efficient and systematic manner, thus minimising the possibility of any areas being overlooked.

Apart from considering the laser display as a series of modules it is also necessary to consider the modules and hazards as a function of the life cycle of the display. The stages of the life cycle can be summarised as follows:

Planning - liaison with "customer" and deciding format

Manufacture - physical manufacture and assembly of components

Testing - make sure everything works
Transport - move the equipment to the intended site
Installation - assembly on site
Alignment - generally optical alignment
Performance - the laser show
Maintenance - carried out by the user on a regular basis
Servicing - usually carried out by manufacturer
Modification (if permanent) - upgrades, etc
Dismantling - take the system apart
Disposal (eventually) - when the system is no longer required.

During the life of the equipment or the show, the different stages of the life cycle will be revisited as shown in figure 6.1. Different people may be at risk from the identified hazards at different stages of the life cycle. Different parts of the life cycle may also take place in different locations with different degrees of control possible. The Pop Guide (HMSO 1993) stresses the importance of the planning stage. Generally, many of the problems experienced at the other stages of the life cycle should have been addressed, or at least foreseen, at the planning stage. It is certainly important that the laser company ensures that any enforcing authorities are involved at this stage in order to identify any specific requirements including written assessments.

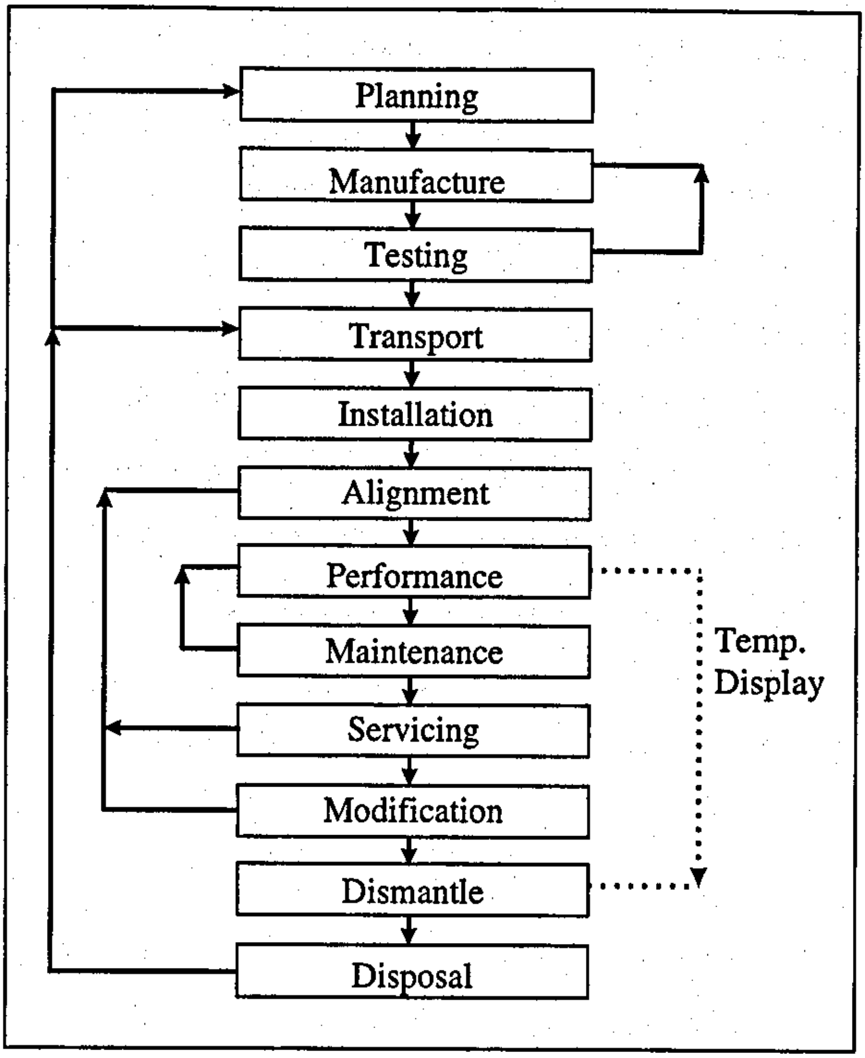


Figure 6.1 Life Cycle of a Typical Laser Display

6.2.1 The Checklist

All parties involved with laser displays had identified a need for a methodology to permit assessments of laser displays to be made. This could be a simple check list but more importantly it is considered that the approach to the assessment must be methodical and systematic, ensuring that all aspects are covered.

A typical laser display can be divided into ten modules, each of which may have hazards associated with it. The mnemonic from the ten sections is SCALE DOVES after the first large outdoor laser display audited by the author, where the laser company projected laser images onto trees in the form of doves to Edvard Grieg's Morning from Peer Gynt.

SCALE DOVES is expanded as follows:

S	Staff involved with the event other than those involved directly with the laser
C	Control system for the laser
A	Audience
L	Laser
E	Equipment associated with the laser
D	Delivery optics
O	Operator
V	Venue
E	External factors
S	Support system

The potential hazards associated with each aspect of the items on the checklist are described in the following sections.

6.2.1.1 Staff

There will always be a number of staff at a venue who will not be directly involved with the operation of the laser. These will include lighting and sound engineers who, if the performance is temporary, may be unfamiliar with the venue, although they may have worked with the laser company at other venues. The venue staff may include management, engineers, audience control staff and vendors. All of these are likely to consider that any safety instructions or notices do not apply to them. Indeed, many will have "All Areas" passes which they will consider will give them access to all areas irrespective of the risks of doing so.

The factors to be considered include the potential for access to the laser, its control system and the laser radiation. The latter will be particularly important during the setting-up and alignment stages.

A further group of staff who should be considered are other third parties, such as first-aiders and merchandise/food vendors. These may not be employed by the venue but are more likely to take notice of safety advice. However, they could be at risk during the setting-up and alignment stage.

The hazards arising from, and to, the staff are summarised as follows:

Unauthorised access to the laser (eg high temperatures, cables, pipes, high voltages, laser radiation)

Unauthorised access to the beam delivery system (primary and secondary) and therefore to the laser radiation and, possibly, moving parts

Unauthorised access to the laser control system (exposure of other persons to laser radiation)

Accidental or deliberate exposure to the laser radiation (possibly through another's actions)

Unauthorised or accidental exposure to high voltages

Unauthorised or accidental exposure to cooling system

Trip hazard arising from various cables and pipes

Mechanical hazard during laser installation

6.2.1.2 Control System

The laser show control system may be sited close to the laser, or one of the lasers if more than one is in use. A central control system may be used or there may be distributed control with some form of communication between the operating staff. Most modern control systems are either personal computer (PC) or microprocessor based. These can introduce considerable flexibility for the laser operator. The signals from the control system to the laser and its optical system need to be considered. If the laser is remote from the control system then the signal cable may pass through the audience. This exposes the cable to potential damage and the resulting action of the laser and its optical system needs to be considered. There may be a radio link. If this is interrupted or interfered with, will the optical system fail to safety?

If the control system is software based then it is very difficult to ensure that all conditions have been tested. A certain set of conditions may not occur for many years but, when they do occur, they may result in a hazardous condition being created. The action of the laser and the optical system should be considered if the computer program 'crashes'.

The integrity of the computer/control system hardware should also be considered. Temporary installations should make use of ruggedised equipment, which will survive the rigours of transport. Again, the action of the laser and optical system need to be considered if the hardware fails.

The hazards associated with the control system can be summarised as:

Failure of the control software
Failure of the control hardware
Links between the control system and the laser(s)
Links between the operators if more than one control system is used

Any one of these eventualities could result in unintentional exposure of persons to laser radiation.

6.2.1.3 Audience

If the laser company complies fully with the published guidance (HSE 1980 or HSE 1996a), the potential for hazardous laser radiation exposure of the audience should be restricted to failure conditions. However, as demonstrated in chapter 3, this cannot be assumed. The analyses in chapter 5 demonstrate how complex quantification of the hazard can be.

The audience may be exposed to laser radiation, either directly (static or scanned beams) or from reflections (intentional or accidental). The pathways for exposure need to be considered carefully and methodically. If blanking plates are used to restrict the directions of the laser radiation, the potential for audience access to the radiation outside of the blanked-off area needs to be considered.

The lasers or their control systems may be within the audience, especially during temporary events. Measures should be introduced to ensure that the audience cannot access any of these. The potential for unruly behaviour should be taken into account: this is less likely during a product launch than during a rock concert, for example.

The audience may have access to items which could be put into the path of the laser radiation, such as reflective, helium-filled, balloons. Control measures to ensure that such items are not for sale at the venue or brought into the venue need to be considered.

The factors relating to the audience are summarised:

Access to the laser radiation
Access to the laser
Access to the optical systems (primary and secondary)
Access to the control system
Audience behaviour
Audience position and control
Potential for introducing reflective items into laser beams
Access to systems associated with the laser, such as high voltages and cooling systems

6.2.1.4 Laser

The potential for hazards from the laser display will relate fundamentally back to the laser. If a class 1 laser product is used, the hazard from laser radiation is considered low. However, if the laser is class 4 then the potential for serious injury exists.

The radiation levels can be compared with the maximum permissible exposure levels. The characteristics required are: wavelength, radiated power, duration of exposure, beam diameter and beam divergence. For entertainment and display purposes the laser will generally be emitting visible radiation. However, the potential use of lasers emitting non-visible radiation, for example in the ultraviolet region, to produce special effects, should not be ignored. Some lasers will also potentially generate radiation in addition to visible wavelengths, such as a frequency doubled neodymium:YAG laser or flashlamp pumped lasers. Good engineering design should ensure that the risk of access to such unintentional radiations is minimised.

The hazards associated with the laser itself can be summarised as:

Laser radiation
Non-laser radiation (including x-rays and ultraviolet collateral radiation)
Mass of the laser
Temperature of the laser housing

6.2.1.5 Equipment Associated with the Laser

The laser requires services to operate. These may include high voltage power supplies and cooling systems. There are also a number of other associated pieces of equipment which assist the display itself. These should all be identified and any hazards recognised. Examples of such equipment are smoke generators used to make the laser radiation visible to the audience and the radio communications equipment used for ensuring that a multi-operator laser show is co-ordinated.

The hazards resulting from the associated equipment can be divided into the following categories:

Hazard to the operator (trip hazards, high voltages, water, etc)
Hazard to other staff (trip hazards, high voltages, water, etc)
Hazard to the audience (hopefully few, but may include smoke/vapour from smoke generators)
Hazard to the laser (eg, water leakage)
Hazard to the optical system (eg, water leakage)

6.2.1.6 Delivery Optics

Although it is possible to have a laser display with a single beam emitted from the laser, it is more likely that there will be an optical system attached to the front of the laser which modifies the direction and/or characteristics of the radiation. In addition, there may be other optical components remote from the laser position such as mirrors or mirror balls.

The primary delivery optics, attached to the laser, are usually controlled remotely. The beam direction may be restricted by the use of blanking plates or by software within the control system. There is the potential for the blanking plates to move and for the software to be programmed incorrectly. There is also the potential for the laser operator to consider that irradiating the audience is not a problem (see appendix B).

The beam direction will probably be controlled by at least two orthogonal mirrors attached to galvanometers. The natural rest position of the galvanometers will have to be considered and the resultant beam position if any number of the drive circuits fail. Beam expanding optics may be used for a beam which is to irradiate a mirror ball. The hazard associated with the beam expander failing to engage needs to be considered. A number of the components in the optical system may present a mechanical hazard to the operator during alignment.

The secondary optics may include items forming part of the structure of the venue or the stage set and may be difficult to predict until the display is performed.

The hazards associated with the beam delivery system are summarised as follows:

Laser radiation exposure of the operator
Laser radiation exposure of the staff
Laser radiation exposure of the audience
Mechanical hazard for the operator during alignment

Fibre optic delivery systems may also be used. There is then the potential for high power laser radiation to travel up to tens of metres from the laser to the aperture. The path of such fibres should be considered, along with the potential for damage, disconnection, etc.

6.2.1.7 Operator

The laser operators are the critical components in a laser show at a temporary event. The safety of the entire laser display system will usually be under their control. The operators should have received adequate training to ensure that they are aware of the capabilities and limitations of the laser display and are aware of the potential safety issues. In a fixed installation, the laser system may have been engineered such that radiation exposure above the maximum permissible exposure levels is not possible and therefore it is possible to have an operator trained to a lesser degree.

The operator may be the person responsible for setting up the laser display, perhaps with a number of other people from the same company. There may be more than one operator for a large installation.

The operator is capable of introducing a number of hazards. The timetable for setting up the display should take into account the requirement to align the optical system before the audience arrives. However, other staff, including the operator, are potentially at risk during this stage.

Hazards connected with the operator are concerned with:

Lack of training
Laser radiation exposure of the operator
Laser radiation exposure of staff
Laser radiation exposure of audience
Lack of safety procedures and systems

6.2.1.8 Venue

Different problems are associated with fixed installations and temporary installations. In the former the initial hazard assessment should identify problems which can be rectified. For temporary installations, problems associated with the venue may not become apparent until the laser display company arrive on site. However, good advanced planning should minimise this.

Hazards likely to be associated with the venue are:

Specular reflecting surfaces
Audience in unexpected places (eg balcony)
Services not available or inadequate

6.2.1.9 External Factors

External factors will include the weather for an outdoor event. Rain will attenuate the primary laser radiation beam but may also introduce many reflecting surfaces. There is also the hazard arising from the high voltages associated with the laser. The weather may have an effect on the attitude of the audience and the concentration of the operator.

Consideration should also be given to other objects or fixtures which may be remote from the venue if they can alter any safety assessment. These will include buildings and aircraft.

6.2.1.10 Support System

The laser and optical system will usually be mounted on some sort of support system. Any secondary optical systems will also be mounted. In a fixed installation, the mountings will be semi-permanent and less prone to unplanned movement. In temporary installations the laser company will generally erect a temporary structure to mount the laser and primary optical system but they may rely on either existing structures or structures erected by other parties involved in the display.

Potential hazards connected with the support system are summarised as:

Instability of the support system
Specular reflections from the support system
Shared access to support systems
Audience access to support systems

6.3 Experience of Using the Checklist in Practice

The Scale Doves model was trialed at thirteen laser displays, both new permanent installations and temporary displays. Although it was possible to identify hazards, the following problems were identified:

> The approach to the assessment was not in a logical order
>
> There was confusion over what was a hazard, and what was at risk, particularly with the audience.
>
> The checklist was accepted by enforcing officers as being better than nothing but was not considered useful by laser display operators.

The laser display companies treated the whole process with suspicion. It was still very difficult to obtain a real impression of the problems faced by the industry on installing fixed or temporary displays and producing performances to, often very tight, timescales. At this stage, contact was made with members of the International Laser Display Association in the United States who, it was considered, would have less direct concern with someone outside of the industry. This was really the starting point for building bridges between the industry and those who have to assess and perhaps regulate their practices.

The UK laser display companies were still producing notifications to enforcing officers using appendix 3 of PM19. However, it was becoming more obvious that such notifications had a small number of pedigrees (probably three). The information provided did not relate to specific venues and often not even to the type of event. Calculations provided were certainly not relevant. In most cases, the calculations had been followed through to give an answer for a single scan effect, which was just below the MPE, but with unjustified assumptions. Typically, it would be assumed that the beam divergence always increased after reflection from a plane mirror, and that the scan rate was hundreds of hertz.

6.4 Developing an Assessment Methodology

It was recognised that any methodology had to be useful to the laser display companies to ensure that they could demonstrate that a risk assessment could be undertaken and, if necessary, presented to enforcing officers. Equally, enforcing officers familiar with the same model would be in a better position to assess such risk assessments.

An important factor which arose during the development of the new methodology was the increasing requirement to provide documented safety assessments in other sectors of the entertainment industry, particularly relating to temporary structures. A small number of laser display companies recognised the benefit in being able to provide similar levels of documentation for their section of the industry. Multi-site entertainment companies were also requiring paperwork to demonstrate the professionalism of their contractors.

The original checklist was modified to include a number of additional parameters and presented in an order which, for most installations, is logical. For each compartment of the model, only the hazards associated with each compartment are considered. However, for each compartment it is still necessary to consider the life cycle of the display, as presented in figure 6.1, and who may be at risk from the hazards at each point in the life cycle.

The methodology is presented in figure 6.2. It can be seen that there is a logical progression from the laser along the optical path and then expanding out from the laser.

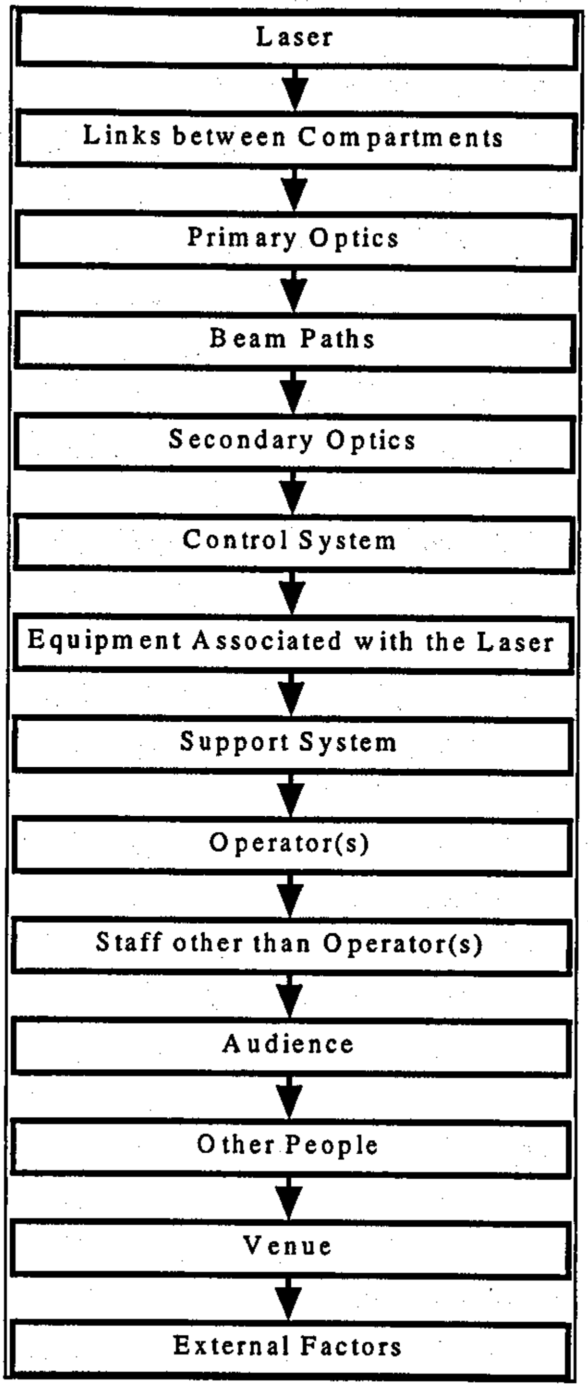


Figure 6.2 Laser Display Hazard Identification Methodology

Many of the compartments are identical to the earlier checklist. The differences are as follows.

6.4.1 Laser

It was recognised that there may be more than one laser and that each would have to be considered, although many hazards will be common.

6.4.2 Links between Compartments

This section of the model was primarily introduced to recognise that the connections between the different sections of the laser display can have hazards associated with them. However, it can also be used as a trigger to consider, for example, how the operator interacts with the control system.

The link between the laser head and the primary optics may be by direct mechanical coupling, via an air gap or through fibre optic cable. It is important to also consider the link between any services and the laser head, and also links between the control system, the optics and the laser.

6.4.3 Primary Optics

It was recognised that the primary and secondary optics had different hazards associated with them at different parts of the life cycle and, in general, would put different people at risk. Therefore, it was important that the difference was stressed by creating different compartments for these different optical systems.

The primary optics will generally be constructed on the premises of the laser display company, requiring only final alignment on site. It is also prudent to encase the primary optics, for safety and to minimise the influence of environmental conditions on the optical components. During normal operation, there should only be a single or small number of actual or potential apertures from the primary optics.

The mounting of the optical components within the primary optical system should also be considered.

6.4.4 Beam Paths

This compartment was introduced into the methodology to ensure that the beam paths are specifically considered. Apart from the justification from the assessments carried out in chapter 5, this also appeared to be an area where the laser companies exhibited a complete lack of understanding of the safety issues.

The assessment should include the paths between the primary optical system and any secondary optics. The previous chapter considered how the hazard from the beam paths should be quantified if personnel exposure is intended or reasonably foreseeable. However, even if beam paths are kept well away from areas occupied by the audience, the exposure of others should also be considered.

6.4.5 Secondary Optics

This compartment considers the mounting of the secondary optics, including any actual or required blanking. Since, by design, the beam path must be to the secondary optical components, the accessibility of both the beam and the optical component should be considered, both during alignment and cleaning, and by, for example, members of the audience.

6.4.6 Control System(s)

This is identical to the earlier checklist as described in 6.2.1.2.

6.4.7 Equipment Associated with the Laser

This is identical to the earlier checklist as described in 6.2.1.5.

6.5 Experience of Using the Methodology in Practice

The hazard identification methodology was tested at nine venues, both permanent and temporary. It was also tested by other NRPB staff to ensure that the breakdown of the problem into the different compartments was logical. The methodology was found to work successfully in identifying the hazards. However, it should be recognised that the model may need to be modified for specific events. Although all lasers displays assessed to date are covered by the model, as technology advances it is likely that the model may need to be extended. This should just be the addition of further compartments.

It was useful to apply the model to a laser display company during the development of new products and the demonstration of existing products. The persons at risk were well defined, and the life cycle and hazard identification methodology are still applicable. This proved to be a useful exercise for the laser company concerned in support of their risk assessment and health and safety policy statement.

The methodology was at an advanced stage of development when HS(G)95 was launched to the industry at NRPB on 8 January 1997. This was seen to be an opportunity to help the industry with a technique to assist with the practical implementation of the new guidance. It was also the first opportunity to raise the questions over the acceptability of audience scanning to a large number of companies at one time. The launch was also attended by managers from venues which use lasers and representatives from equipment manufacturers. Twelve of the largest laser display companies had the opportunity to comment on the new guidance document and the views on audience scanning. The companies felt that HS(G)95 did not meet either their requirements nor those of the enforcing officers. Each, as stated before, preferred a more prescriptive approach, with clear guidance on what can and cannot be done, and therefore little flexibility for interpretation which was considered to be inconsistent throughout the UK.

The result at the end of the seminar was the determination of the industry to form a professional association to look after their interests. Thus the Entertainment Laser Association (ELA) was formed, probably more as a pressure group than anything else. That this body should have been formed at all is significant. Most of the member companies had been spawned from a small number of pioneering laser display companies as the result of disagreements between individuals. They were also operating in a fiercely competitive market against a general view that lasers had had their day and often were staged in a less than professional manner.

It is interesting that some of those present at the meeting supported the views presented and particularly concerns over insurance issues for intentionally exposing the audience to laser radiation levels in excess of internationally agreed MPE levels. These included the venue managers and one of the laser display companies who already operated to a quality system for their non-laser work, such as lighting and sound installation.

ELA formed a number of sub-committees, including one covering safety. Presentations of the hazard identification methodology were made both to the sub-committee and to the ELA Committee.

6.6 Conclusion

A methodology has been developed for the identification of the hazards associated with the use of lasers for entertainment. This has evolved from a simple checklist to a logical methodology which considers the various modules of a laser display (figure 6.2) as a function of the life cycle and the persons at risk.

The involvement of the laser display companies with this research has been initially to be suspicious of the rationale behind any attempt to formalise the safety aspects of their industry. It was necessary to seek information and comments from non-UK laser companies, such as members of the International Laser Display Association, who felt less threatened by any involvement in their industry.

The introduction of revised guidelines in the UK (HS(G)95) and internationally (IEC

60825-3) should have provided the opportunity for clear statements of the safety requirements for laser displays and how these should be demonstrated. However, both documents failed to achieve this through a more general goal-setting approach. Neither document was developed with any significant input from the industry. However, the launch of the UK guidelines in January 1997 did trigger the formation of a UK-based professional body for the industry.

The hazard identification methodology was presented to the industry both formally and on an individual basis as work continued alongside a number of laser display companies and enforcing officers as displays took place throughout the UK.

Identifying the hazards is not the end of the story. It is necessary to follow this through to an assessment of the risks and finally to management of any residual risks. This, again needed to be supported by both the industry and the enforcing officers. The process will be explored in the following chapter.

7. Risk Assessment

7.1 Introduction

The hazard assessment methodology developed in chapter 6 is not the end of the story. It is necessary to use this information to assess the risk from the use of lasers, determine control measures to eliminate or reduce the risk, and to manage the residual risk.

There is a legal requirement in the UK for employers to undertake a suitable and sufficient assessment of the risks to which their employees and others are exposed (HMSO 1992). It is important to present the conclusions in a form which is meaningful to the employer, ie assists with risk management, and to others, such as enforcing officers so that informed decisions on the adequacy of control measures and residual risks can be made. There is currently only a legal requirement to make a record of the significant findings of the risk assessment under the Management of Health and Safety at Work Regulations (MHSWR) (HMSO, 1992) if the employer employs at least five employees. It is recognised that many laser display companies could fall below this threshold. However, enforcing officers may be able to use powers under entertainment licensing legislation to require a written record as a reasonable licence condition.

This chapter considers an ideal example of a risk assessment for part of the laser display and a means of presenting the data. However, it is accepted that the time constraints may make such assessments unlikely by the laser companies unless specifically requested by the enforcing authorities or the venue management. Therefore, a more critical risk assessment methodology is presented whereby a decision can be made on whether the risk can be assessed reasonably, or whether further information is required. Such a process should allow an enforcing officer to follow a methodology to the limit of their expertise and be confident of seeking further advice, which will normally be the analysis of information already provided where particular expertise is required. This approach should provide a means of analysing whether the risk assessment is suitable and sufficient. It is strongly considered that it is more important for the laser display company to demonstrate an understanding of the risk and to be able to present conclusions based on actual data rather than to be able to present a microscopically detailed assessment. Such an approach should also meet the requirements of only needing to present the significant findings of a risk assessment.

7.2 Risk Assessment Methodologies

Formal risk assessment methodologies have been developed for industries where the risk is either actually high, demonstrated by a number of adverse incidents, or perceived to be high. Nuclear power plant operators and chemical production companies have developed sophisticated models to evaluate the risk to their employees and the public around facilities. Most of this work is carried out at the planning stage of new plants (Kletz 1992). Engineers also use risk assessment techniques to look at failure modes for machinery or processes, ie to determine the reliability (Modarres 1993). Here, the risk to personnel may be trivial but the commercial risk may be important.

When developing a manufacturing process or a power plant, the investment and return is such that significant effort to determine the risks can be justified. Laser displays are generally provided on a very tight budget within a short timescale. The use of formal techniques such as HAZAN or component failure analyses may not be justified, except for a major permanent installation which is likely to attract large audiences over several months or years. It is also questionable whether the employees of the laser display companies will have the expertise to carry out such assessments. Concerns had been expressed by employers in other industries who had considered that the MHSWR required them to undertake assessments which produced numerical values for risk to different critical groups. These concerns were addressed by the Health and Safety Executive producing a practical guide to risk assessment at a level which would be reasonable in many industries (HSE 1994). Essentially, the guide suggested that there are five steps to any risk assessment: identify the hazards, decide who may be harmed, evaluate the risks, record the findings, and review and revise the findings. A methodology for completing steps one and two has already been presented in chapter 6. The analyses from chapter 5 will provide input to step 3 for the laser radiation.

7.3 Risk Assessment in Practice

Assessing a complete laser display from the planning stage through to disposal will be a time-consuming process. However, much of the assessment will be common between installations carried out by a laser display company. This is particularly apparent when the life cycle of the laser display is considered (section 6.2). The work carried out at the laser company's premises is likely to be similar and, generally, will be under the control of the employer. Transport will also be similar. The major difference is between venues and the detail of the actual laser display equipment. However, for a touring show, the differences are only related to the venue.

A significant benefit of a company using the same approach for all of its work is that the enforcing authorities, promoters and venue managers become familiar with the process and the way the information is presented. If a common format can be agreed between companies then the net benefits are even greater.

7.3.1 Who is at Risk?

The identification of the hazards in chapter 6 demonstrates that many of these hazards have a risk of death associated with them, such as high voltages and working at height. However, it is important to recognise that the persons at risk from these hazards are generally either the employees of the laser company or other employees associated with the event. The total number of people at risk from these hazards is therefore small. Coming back to the premiss from chapter 1, the average family attending an entertainment event assumes that their safety is assured. The audience will generally number far more people than the employees. What is the risk that a member of the audience, or indeed another non-employee, could be injured as a result of the activities associated with the laser display? The risk of an individual member of the public being injured or killed will depend on the probability that they will be exposed to the respective hazard.

It is an interesting human characteristic that the number of people injured or killed features highly in the tolerability of risk from an activity to the extent that killing one employee of the laser company is generally more acceptable then injuring a large number of people in the audience.

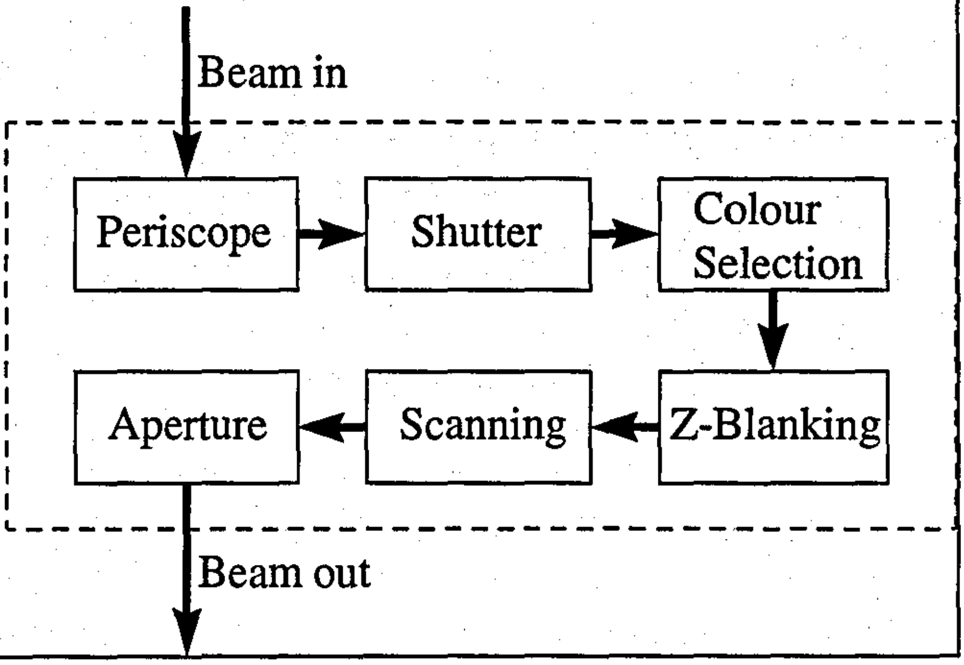
The main hazard that the audience are potentially exposed to is from the laser beam paths, ie the laser radiation. If there are secondary optics in the audience area then these may have hazards associated with them. It is also possible that there may be links between the components of the laser display, such as control cables, passing through the audience. However, the laser beam path has the greatest potential to affect the largest number of people. The range of outcomes following exposure to laser radiation is from no effect, through sub-damage-threshold effects, such as distraction and after-images, to actual physical damage. The result of any damage will depend on the damage site, even within the target. If the target is the eye then damage of the macula is likely to result in the loss of central vision. Even damage outside of the macula may result in vision degradation, or even blindness if the communication pathways to the optic nerve are damaged. Such damage obviously effects the quality of life of the exposed individual. However, there are also likely to be other implications. A typical insurance payment for the loss of sight in one eye is about £30,000 in the UK. An insurance claim is likely to result in a critical review of the risks from the industry by the insurance companies, which may have far reaching implications for the use of lasers in the entertainment industry.

Recognition of the key risk issues allows the enforcing officer to identify where effort is required to determine if the risk assessment carried out by the laser company is adequate and that the hazards have been adequately controlled and the risks are minimised. It should be possible to codify this taking account of the hazard identification methodology to permit assessments to be made in a reasonable time. However, this should not detract from the laser company's duty to carry out a suitable and sufficient assessment of the risks which cover public, and others', exposure to hazards.

7.3.2 Example Risk Assessment

An example of the level of detail that is considered appropriate is presented here for a simple primary optical system, as one compartment of the hazard identification methodology (chapter 6). Laser radiation is fed in to one end of the system and the output is through an aperture. An outline of the components of the system is in figure 7.1.

Figure 7.1 Schematic of Example Primary Optical System



Assume that the input laser beam is from a krypton-argon laser with three wavalengths - 488 nm (blue), 514.5 nm (green) and 647.1 nm (red). If these have been balanced for the photopic response of the eye (section 3.1.1) then the input beam will be perceived as white light. The periscope is used to adjust the beam height between the laser and the optics of the primary optical system. This consists of two planar, front surface reflection, mirrors. Adjustment of height and angle of each mirror is possible. All of the remaining optical components are at a fixed height. All components are mounted on a solid metal base using at least two bolts screwed into tapped holes in the base.

The shutter consists of a solenoid with a black beam stop mounted in the end of the shaft. The default position is down with the beam stop in the beam path: a drive voltage is needed to pull the beam stop up out of the beam path. The colour selection consists of three rotary actuators with dichroic mirrors which are matched to the three wavelengths, ie the 488 nm dichroic will reflect the 488 nm wavelength but transmit the other two wavelengths.

The z-blanking consists of a lens which focuses the nearly parallel beam from the periscope into the mirror of a galvanometer. The galvanometer and mirror position is set so that the beam is reflected or transmitted, ie the edge of the mirror interrupts the beam under program control. A second lens recollimates the beam after the galvanometer. The transmitted beam is positioned in the centre of the mirror of the first scanning galvanometer. The reflected beam from this mirror is then incident on the mirror of the second galvanometer. The beam from this mirror is then output from the primary optical system via an exit aperture.

It is necessary to identify which parts of the life cycle are relevant to the primary optical system and the persons likely to be at risk at each stage of the life cycle. An example of such an assessment is presented in figure 7.1, below.

STAGE OF LIFE CYCLE	HAZARDS	PERSONS AT RISK
Planning	None	No-one at this stage but consideration of the remainder of the life cycle should reduce the risk
Manufacture	Mechanical (tools, sharp edges, weight of items), electrical, heat (soldering iron), chemical (cleaning fluids)	Employees, visitors (perhaps including client)
Testing	Mechanical (moving parts), electrical, water, laser radiation	Employees, visitors (perhaps including client)
Transport	Mechanical (weight, sharp edges)	Employees
Installation	Mechanical (weight, sharp edges), electrical	Employees, others in the vicinity but generally employees of other employers
Alignment	Mechanical (moving parts, weight, tools), electrical, water, laser radiation	Employees, others in the vicinity but generally employees of other employers. Public, including the audience.
Performance	Mechanical (moving parts), electrical, water, laser radiation	Employees, performers, audience, other staff

STAGE OF LIFE CYCLE	HAZARDS	PERSONS AT RISK
Maintenance	Mechanical (moving parts, weight, tools), electrical, laser radiation, heat (soldering iron), chemical (cleaning fluids)	Employees, others in the vicinity but generally employees of other employers
Servicing	Mechanical (moving parts, weight, tools), electrical, laser radiation, heat (soldering iron), chemical (cleaning fluids), water	Employees, others in the vicinity but generally employees of other employers
Modification	Mechanical (moving parts, weight, tools), electrical, laser radiation, heat (soldering iron), chemical (cleaning fluids)	Employees, others in the vicinity but generally employees of other employers
Dismantle	Mechanical (weight, sharp edges), electrical	Employees, others in the vicinity but generally employees of other employers
Disposal	Mechanical (weight, sharp edges)	Employees, any other person

Table 7.1 Hazards and Persons at Risk from Primary Optical System

It is now necessary to evaluate the control measures in place to ensure that personnel are not exposed to the hazards. Again, these are likely to be different at different stages of the life cycle.

The hierarchy of control measures should be as follows: prevent exposure to the hazard by eliminating the hazard; substitute the activity for one that presents a reduced hazard; enclose the hazard; reduce the number of people potentially or actually exposed to the hazard; or provide personal protective equipment. Training will also be an important control measure. However, this may only be effective for employees of the laser display company and, exceptionally, performers. Certainly an audience cannot be expected to be trained or to take notice of safety instructions.

7.3.2.1 Manufacture

One of the primary control measures during manufacture is the training of the employee undertaking the work. However, many of the hazards identified at this stage of the life cycle in table 7.1 can be controlled at source. The use of good quality components, including fixings, with the correct tools should reduce the risk of injury. Consideration should be given to appropriate connection techniques, ie whether to solder components or dry mount, and whether to crimp or solder leads. If a soldering iron is used, it should be used with extraction and be stored in an appropriate base unit. Where cleaning, or other chemicals are used, the COSHH assessments (HMSO 1994c) should be undertaken prior to the chemicals being used. If possible, chemicals with a trivial or low risk of ill health should be used.

7.3.2.2 Testing

At the testing stage the primary optical system is likely to be connected to a control system and probably a laser. A number of the components move, or will need adjustment. The minimum laser power necessary to undertake the alignment and testing should be used. It should be recognised that eye exposures at levels below the maximum permissible exposure level may cause dazzle, especially when working in reduced ambient light conditions. With the laser on, and covers removed from the primary optical system, the risk of exposing other people to the laser beam also needs to be recognised. The simplest control measure is to restrict access to the area where the work is carried out. However, this should be balanced against the risk to the engineer working alone.

There may be mains voltages within the chassis of the optical system, although most units will operate at 24, 12 or 5 V DC maximum. Where there are mains voltages, it would be reasonable to enclose these locally to minimise the risk of accidental contact with live conductors.

At some stage, the primary optical system is likely to be tested with the full power from the laser to be used in the display. This could identify stray reflections which were not apparent at the lower power. Again, it will be important to reduce the number of people at risk and to ramp the power up, where possible, so that unintended beam paths can be eliminated as soon as they have been identified.

7.3.2.3 Transport

A well engineered system should not have sharp edges. However, there is still the risk of trapped fingers and manual handling considerations both when the optical system is loaded into the transport case, and when the case is loaded into the vehicle. Simple control measures include wheels (which can be locked) on the flight case and a case design which does not require bending over and lowering the optical system into a case. A flat base unit with a lid integral with the sides may be a suitable solution.

7.3.2.4 Installation

The first part of the installation is to unpack the equipment. It then has to be located in position. These both have manual handling implications. It is also possible that the installation is at height or in restricted spaces. Planning should have identified any particular issues here and appropriate control measures implemented.

The weather, which may be too hot, cold or wet, may have an impact on the risk to persons at the installation stage. Appropriate clothing, including footwear, hats and gloves, may be required. However, any risk of using such measures should also be considered.

The services to the optical system may present a risk to the installer and others. These will include power and signal connection cables.

7.3.2.5 Alignment

Most of the alignment of the optical system should have been carried out before the unit was transported. However, there will still be a degree of final alignment. Many of the risks and control measures will be similar to the testing carried out before installation. However, there may be the risk of exposing more people, including non-employees. The hazard likely to present a risk over the greatest distance is the laser radiation. The risk of accidental exposure can be reduced by the use the minimum power necessary to do the alignment and local shielding. The latter may include a beam stop placed at some distance in front of the beam aperture. This beam stop also assists with the alignment process. The minimum power necessary to undertake the alignment will depend on ambient light conditions. Under extremely bright conditions the input power from the laser may need to be of the order of 1 W, especially out of doors when the beam needs to be aligned with secondary optical components. Under these circumstances it may be necessary to remove all unnecessary people from the area while the alignment takes place. This eventuality should be considered at the planning stage, especially for events out of doors.

7.3.2.6 Performance

In order to minimise the risk of exposure to any of the hazards associated with the primary optical system during the performance local shielding should be used. This will include shielding over some optical components, such as the dichroic mirrors to ensure that the reflected beams are suitably dumped. A cover should be placed over the complete optical system so that the only apertures are the input aperture for the laser and the intended exit apertures.

It should not be possible for non-employees to get access to the primary optical system, and certainly not to the exit apertures.

The emergent laser beam is a residual hazard which should be controlled by its position in relation to accessible areas. Engineering controls such as blanking plates should ensure that, even in the event of a component or control system failure, the beam cannot access audience areas. It is recognised that some operators wish to undertake audience scanning and that the blanking would not permit this. However, with reference to the arguments in chapter 5, it would be reasonable to undertake audience scanning only with further consideration of control measures. For example, the beam used for audience scanning passes through a separate beam path, ie through a diverging lens, and exits from the primary optical system through a dedicated aperture.

7.3.2.7 Maintenance, Servicing and Modification

The control measures for the hazards associated with maintenance, servicing and modification are similar to those for testing, installation and alignment with due consideration to the location where the work is carried out and the persons likely to be at risk.

7.3.2.8 Dismantle

Dismantling the equipment is essentially the reverse of the installation with two possibly significant factors: the crew are likely to be tired and, if out of doors, it may now be dark,

7.3.2.9 Disposal

The disposal of the optical system should present no more risks than the disposal of any other engineering components. The most appropriate route of disposal will generally be recycling with the components re-used on other systems. However, as the components become obsolete they will be disposed of through normal disposal routes.

7.4 Presenting the Risk Assessment Conclusions

As has already been identified, there are different audiences for the conclusions from the risk assessment. The company will have a legal requirement to record the significant findings from its risk assessments if it has more than five employees (HMSO 1992). However, the laser display company may wish to present its assessment in a written form for any or all of the following reasons:

- compliance with health and safety legislation
- compliance with licensing legislation
- staff relations
- customer relations, including the presentation of a professional image
- improved efficiency and effectiveness

The Health and Safety Executive's (HSE's) former guidance (HSE 1980) provided a suggested proforma for the presentation of the basic information in support of a laser display notification to the enforcing authorities. As has already been described in Chapter 3, although these were used by some laser companies, the information was generally not adequate to allow a third party to assess the safety of the display.

The Australian code of practice (NHMRC 1995) provides a display safety record proforma which was developed during the course of this research. The proforma has the following sections:

- Responsible persons
- Training
- Laser System
- Venue
- Display Plan
- Hazard Assessment
- Protective Equipment
- Display Maintenance and Routine Checks
- Statutory Authority Approvals and Restrictions

Although a good starting point, there is little advice on how this information should be presented.

The revised HSE guidance (HSE 1996a), which the author contributed to, refers to hand-over documentation. This is recognised as being "good practice" rather than to meet a specific requirement. A list of what the hand-over documentation should include is:

- calculations and supporting measurements of exposure levels at defined positions within the display area, in keeping with HS(G)95, or otherwise demonstrating the overall safety of the installation;
- clear instructions on the use and effect of display controls;

- details of all permissible display effects, their safety implications and the constraints on their use;
- information on manual shutdown and surveillance requirements;
- information on automatic emergency shutdown systems, their mode of operation, maintenance requirements and function verification;
- details of routine servicing and maintenance procedures, their frequency, who should carry them out, and details of protective eyewear and/or clothing required;
- details of routine adjustment and alignment checks to be carried out by the user, to include frequency, record keeping and corrective action requirements: external optical component checks are especially important;
- operator experience and training requirements;
- the supplier's address and telephone number or those of its LSO; and
- any special conditions to be observed.

The guidance also recognises the value of scale diagrams and/or photographs and that the information should be presented in a form which is adequate for independent verification of emission safety by the enforcing authority.

There is no requirement to provide hand-over documentation under this guidance if the installer is also the user.

The international guidance (IEC 1995), which the author contributed to, refers to a display safety record which should include:

- all relevant safety information relating to the design, installation, alignment and operation of the display;
- the names and addresses of designers, installers, modifiers, operators and owner of the laser display equipment;
- any operation and display approvals and restrictions issued by regulatory authorities (both local and national); and
- laser equipment manuals conforming to 6.1 and 6.2 of IEC 60825-1.

It was recognised that the laser display companies would only draft documentation if either there was a specific legal requirement to do so, or if there was a commercial benefit to them. Therefore, the proposed Laser Display Safety Record tries to address this latter issue while also addressing the general requirements to record a risk assessment, meet the requirement of national guidance and comply with licensing legislation.

7.4.1 Laser Display Safety Record

The format of the Laser Display Safety Record has evolved from a need to provide a document which can be assessed, and be useful, to persons other than those who draft it. The final format uses a modular approach and is ideally suited to filing in a ring binder. As will be discussed later, this format also supports sub-sets of the Record, which can be used for specific purposes.

The laser display company should have a safety policy statement as required under Section 2(6) of the Health and Safety at Work etc Act 1974 (HMSO 1974). The Laser Display Safety Record could also be considered part of that statement.

The outline Laser Display Safety Record presented here only covers the laser display from the time it leaves the laser company's premises until it returns after a temporary installation. However, it can be seen that the format can be modified to cover permanent installations or, indeed, operations at other stages of the life cycle, including manufacture and testing at the company's premises. In particular, such a Record should exist for any installed demonstration facilities at the company's premises.

Suggested section headings for the Laser Display Safety Record are presented in appendix E.

7.4.2 The Laser Display Safety Record in Practice

The Laser Display Safety Record has been used by one of the major UK laser display companies for a number of events. A number of benefits were identified:

- the format was useful for event managers and enforcing officers
- the laser display company manager was able to identify a number of shortcomings with his own operations and introduced a number of additional control measures to reduce the risks to his staff and others
- the process of drafting the Record gave the management of the laser display company a better understanding of the problems faced by enforcing officers, who have to assess such displays
- the Record provided a metric against which to carry out internal audits.

The format of the Laser Display Safety Record was not without criticism. Each Record could fill an A4 ring-binder file. Preparation of the file also took significant effort. However, the investment in developing the file should mean that subsequent files can be built up from a series of modules. Many parts of each operation are common. An example file is presented as Appendix F.

It is also recognised that many enforcing officers will not welcome a large quantity of paperwork to assess. However, this is not the main reason for drafting the file. The value of the effort required to draft the file must rest primarily with the laser display company. They have the responsibility to ensure that the risks are either eliminated or reduced to an acceptable level.

It is possible to use a sub-set of the Laser Display Safety Record to provide an indication of the risk assessment carried out for a particular display. Fundamentally, the enforcing officer will want to know what will happen, where it will happen and when. They will also want to know the significant findings from the risk assessment. This is essentially Section 1 and Section 5.7 of the file.

The Laser Display Safety Record (LDSR) represents an ideal situation where time and effort are of no object. However, most decisions which need to be made by enforcing officers are made under less than ideal conditions with time being the main problem. It was also recognised that they still needed to be reviewed by someone with significant knowledge of the subject to make a decision on the bottom line, ie whether the risk is acceptable and the laser display should be permitted to proceed.

The LDSR was adopted in a modified form by the Entertainment Laser Association and used by their members for providing information in compliance with the requirements of HS(G)95. This should be seen against a background of a view that notifications were not required under HS(G)95, compounded by some animosity due to the industry not taking an active part in drafting the guidance. If the methodology was working perfectly then it should be possible to assess the laser display from the information provided.

Assessments provided by various companies suggested that they were happy to complete the non-contentious sections, ie details of where and when the laser event was taking place. It appeared that the old PM19 appendix 3 information was being re-worked to fit the LDSR format. Even information on the laser equipment was not complete. Risk assessments were included as far as the example presented in appendix F, even if not relevant. This had always been a concern with presenting a worked example since, as stated in chapter 3, the number of PM19 appendix 3s appeared to be small, giving the impression that many enforcing officers were happy to receive some paperwork irrespective of the quality and relevance to the specific event.

The problems with using the LDSR suggested that the whole risk management methodology was not yet mature.

7.5 Assessing the Significant Risks

At the International Laser Display Association annual meeting in Lincoln, Nebraska, in November 1997, the author presented the hazard identification methodology and the Laser Display Safety Record to an international audience. This was significant because most of those present were from the USA, where audience scanning is very restricted and very much the exception. Risk assessment is not generally used in US legislation but a number of those present could see the benefit of having a methodology for assessing the risks and presenting the significant findings to regulators. They saw this as a means to being able to demonstrate that, under certain well-controlled conditions, it would be acceptable to carry out audience scanning. This, of course, was in marked contrast to UK and European countries where the practice was widespread and it was considered that attempts were being made to restrict an accepted part of most laser displays. At the end of the ILDA meeting, the President stated that he wished to see the industry develop an international laser safety guide. Subsequent to the meeting, an international laser safety forum was formed from the interested parties.

Despite an agreement internationally that the safety issues had to be addressed, there were many views on the levels of risk to which the audience in particular was exposed. It was considered that different standards existed in different countries and many of the misunderstandings regarding audience scanning exposure conditions prevailed. This provided extra justification for a risk assessment methodology which could get to the heart of the real risk issues and be interpreted throughout the world. In short, the negative attitude of many ELA members had been replaced by an international desire to address the real safety issues to be able to demonstrate that the industry could operate in a safe manner without risk to the audience.

7.5.1 Who is at Risk?

The hazard identification methodology recognises that there are different people at risk from exposure to the hazards. This can be summarised into zones of people:

- Laser company employees
- Other employees
- Performers
- Audience
- Other people

Not all laser display events will have people from all categories and, indeed, the life cycle will also be important. Using these categories of people, who will generally be in certain specific positions in the venue as a function of time, it is possible to identify where the real risks exist as a function of the hazard identification methodology, life cycle and zone. Folded into this the number of people at risk and the outcome will need to be considered.

A three dimensional representation of the risk assessment methodology is shown in figure 7.2.

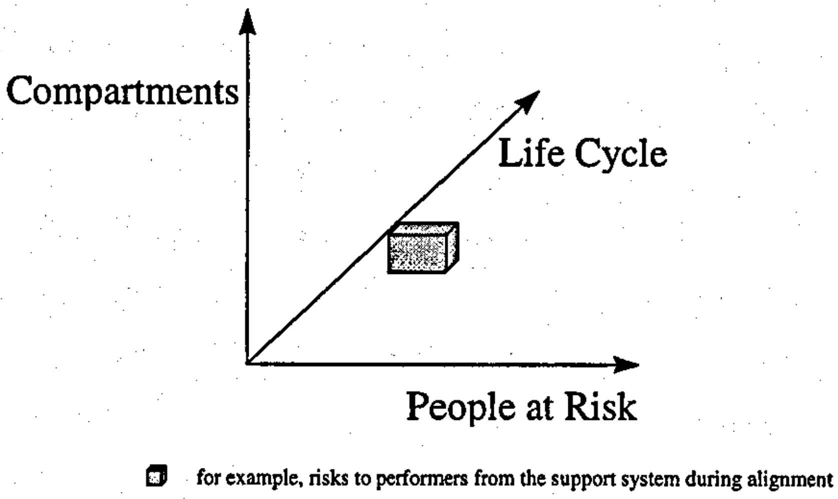
There are a number of ways of expressing the probability of persons being exposed to a risk, the outcome and the number of people at risk. For this analysis, a numerical system is used whereby a larger number represents a greater problem. A risk factor can be calculated by multiplying the three parameters. It is likely that different outcomes will have different risk factors. For this analysis the largest numerical risk factor is used. The parameters are assigned numerical values as follows:

Probability: 1 - Improbable
2 - Possible
3 - Likely
4 - Very likely
Outcome: 1 - No injury
2 - Minor injury
3 - Major injury
4 - Death
Numbers: 0 - None
1 - 1 Person
2 - 2 to 5 People
3 - 6 to 20 People
4 - Greater than 20 People

7.5.2 Results

An analysis is presented as a function of the life cycle and the compartments of the hazard identification model, for each of the zones of people considered at risk, for a temporary outdoor display (figures 7.3 to 7.7) and for a permanent indoor installation (figures 7.8 to 7.10). For comparison, the z-scales are identical for each zone within each event. The number of zones for the permanent installation is less than the temporary display. It is also assumed that intentional audience scanning forms part of the outdoor display, but not the indoor display. The public are also admitted during the alignment of the outdoor display, as was experienced at event B in appendix B.

Figure 7.2 - Three Dimensional Representation of Risk Model



The analysis of the risks in the manner presented in figures 7.3 to 7.10 gives a rationale for focusing the management of the risks. It is significant that the public are rarely at risk of death from a laser display, whereas the activities of the laser company may put themselves and other employees in the vicinity at such risk. Once the laser display reaches the performance part of the life cycle the analysis of the risks is simplified and, as suggested from figures 7.3 to 7.10, the main issues are the exposure to the laser radiation and in particular whether such exposures are intended or reasonably foreseeable. Taking the three-dimensional presentation of the risk assessment issues from figure 7.2, this can be redrawn with the key issues as presented in figure 7.11. In essence there is a bottom line - are the audience at risk from the beam paths either through intentional or accidental exposure.

Figure 7.3 Risk Matrix - Laser Company Employees Temporary Outdoor Display

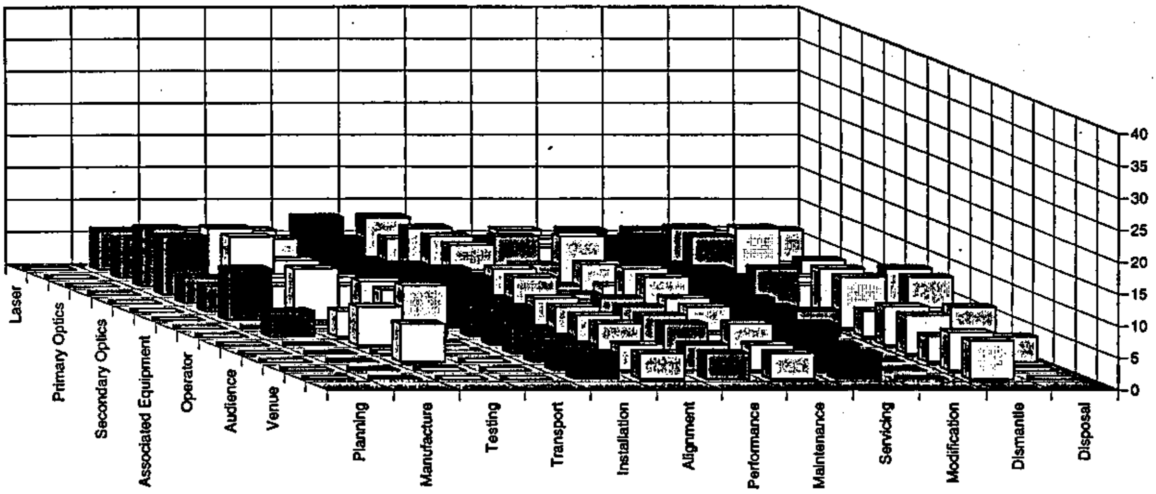


Figure 7.4 Risk Matrix - Other Employees Temporary Outdoor Display

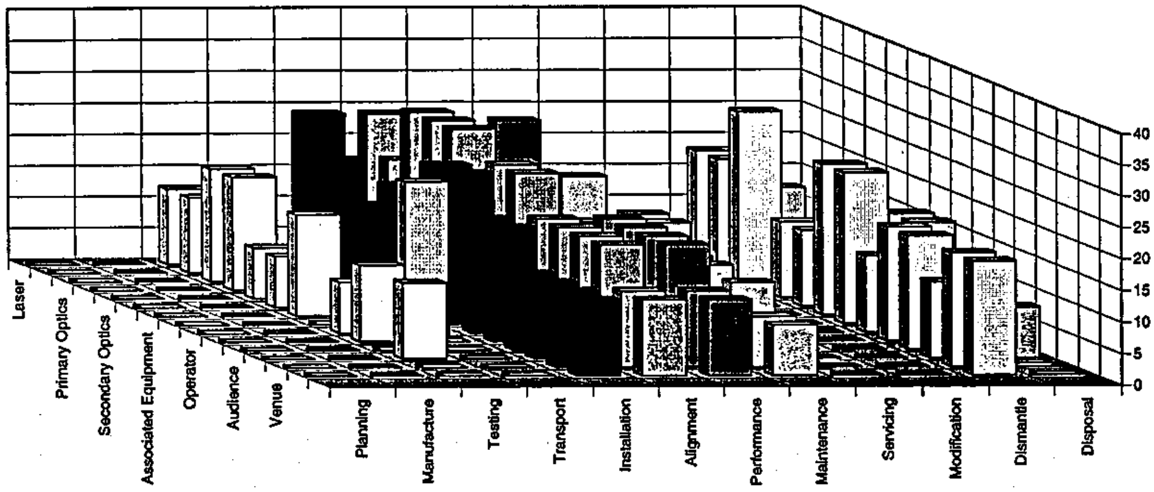


Figure 7.5 Risk Matrix - Performers Temporary Outdoor Display

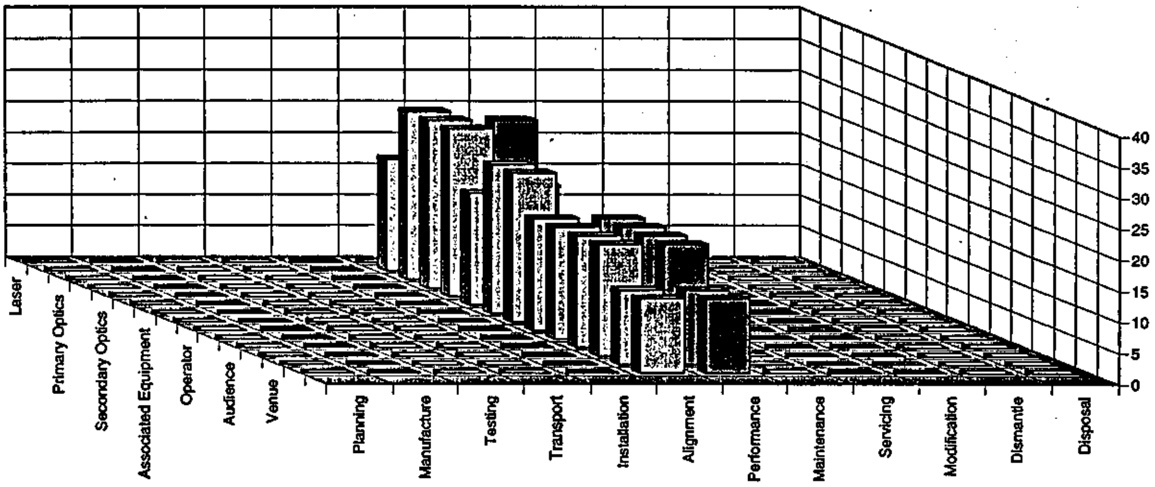


Figure 7.6 Risk Matrix - Audience Temporary Outdoor Display

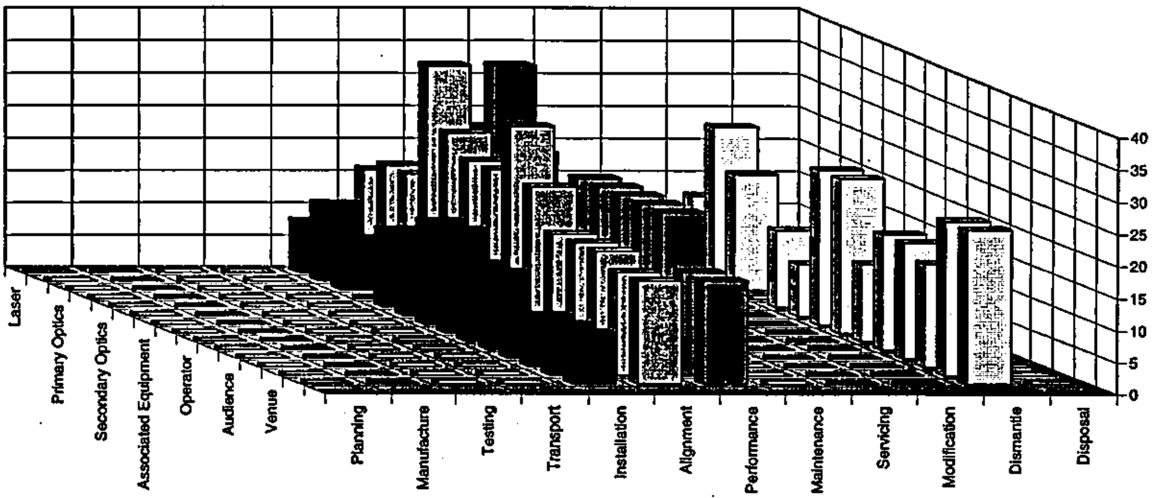


Figure 7.7 Risk Matrix - Other Members of Public Temporary Outdoor Display

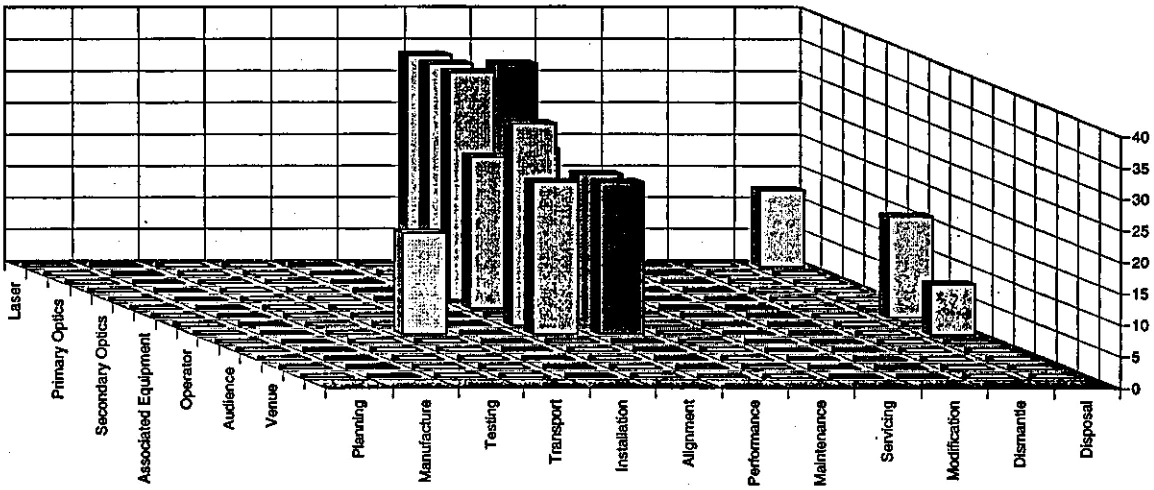


Figure 7.8 Risk Matrix - Laser Company Employees Permanent Installation

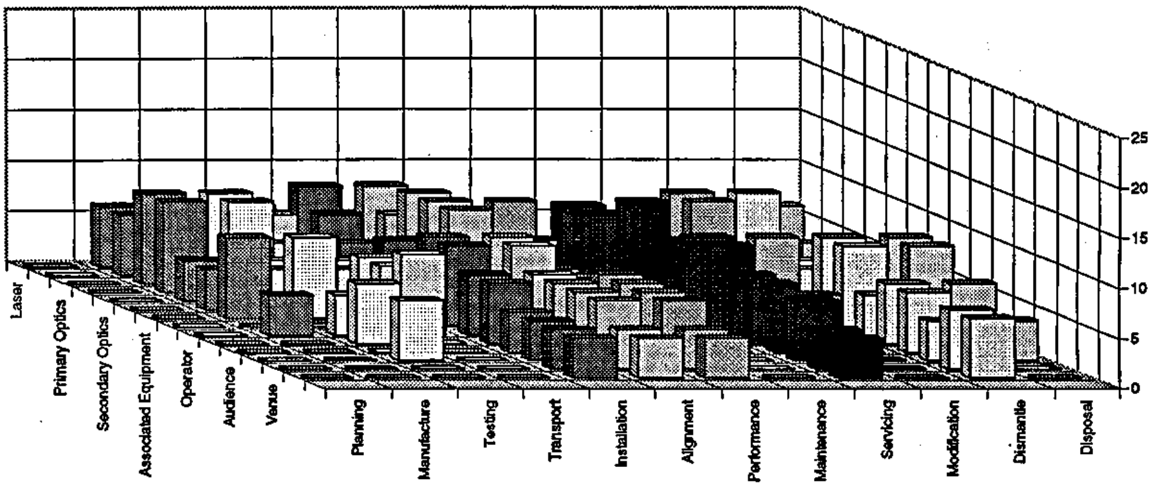


Figure 7.9 Risk Matrix - Other Employees
Permanent Installation

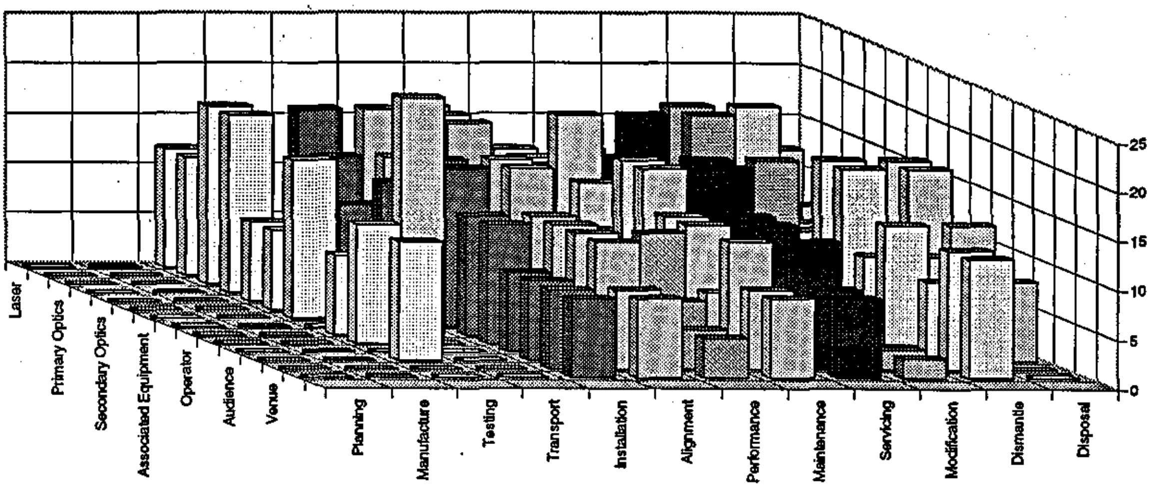


Figure 7.10 Risk Matrix - Audience

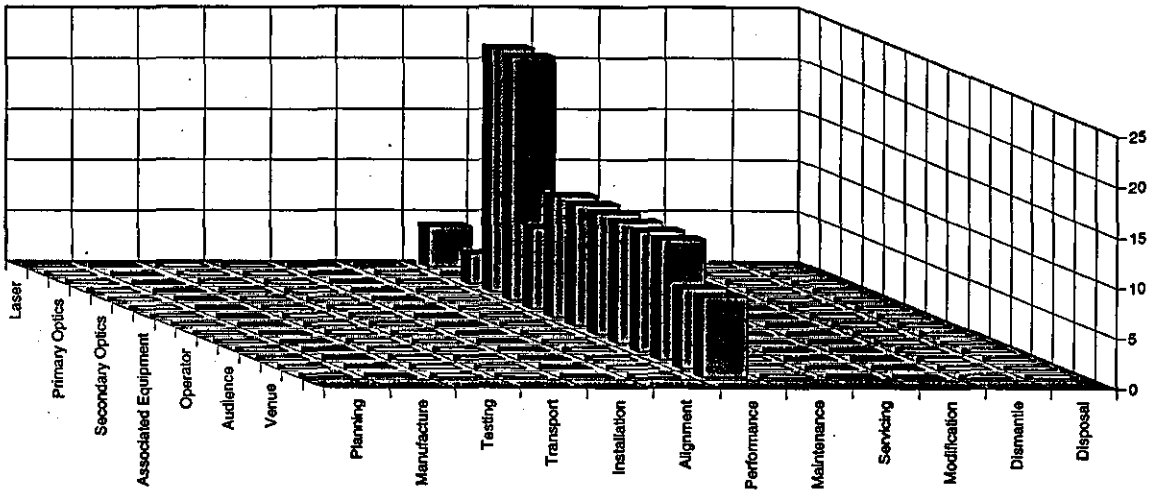
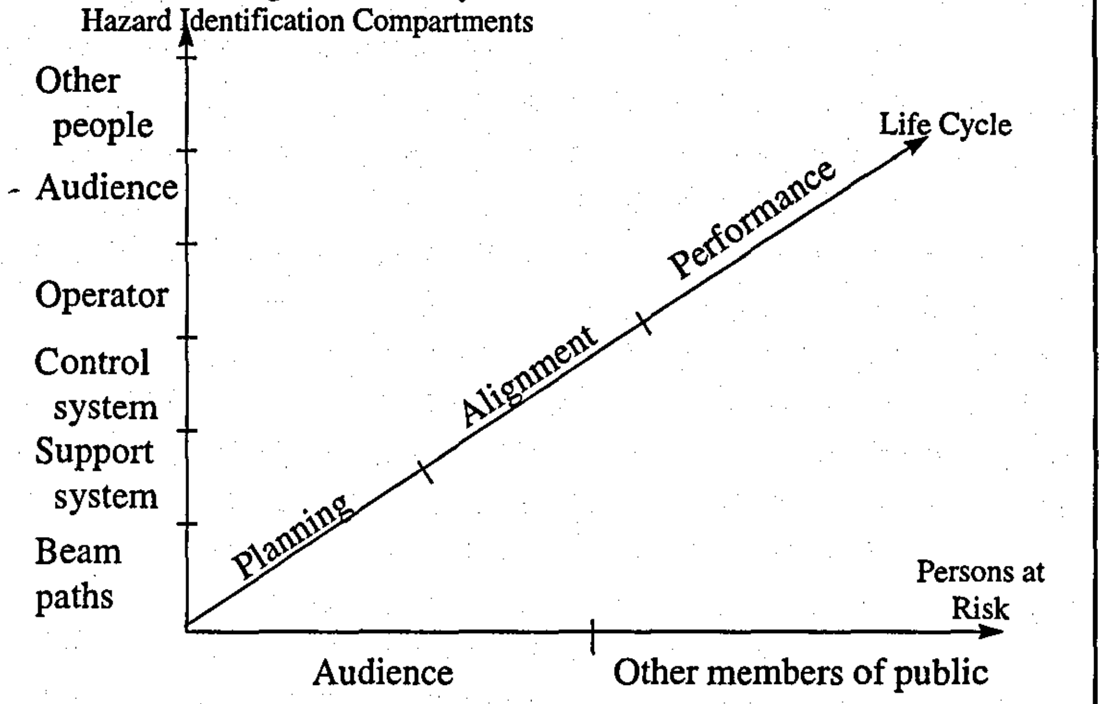


Figure 7.11 Key Risk Assessment Issues



7.5.3 Codifying the Risk Assessment

The former HSE guidance on the safety of laser displays (HSE 1980) attempted to provide a proforma, specifically aimed at the enforcing officer for demonstrating compliance with health and safety requirements. The goal-setting approach of the revised guidance (HSE 1996) requires a risk assessment to be carried out. The feedback from chapter 4 has shown that the enforcing officers were not able to apply formal training on assessing laser displays but were still seeking advice and reassurance each time a laser display took place. Codifying the assessment process should assist the enforcing officer to carry out most, if not all, of the assessment of risk management for a given event. This could be programmed into a decision support software package. Building on the experience gained with applying the risk assessment methodology developed here, the key issues can be distilled. Generally, the enforcing officer will only be concerned with the stages of the life cycle which put the public at risk, although it should be appreciated that activities and decisions made at the other stages of the life cycle may impact on public safety.

The primary question will be "does audience scanning form part of the laser display?". If the answer to this is yes, then the risk assessment needs to concentrate on this issue. If intentional exposure does not form part of the display then the failure modes which could result in audience exposure need to be considered. The key issues for a decision support system simplify to the following.

- Whether intentional personnel exposure to laser beams takes place
- The reasonably foreseeable incidents which could expose personnel to the laser beams
- The integrity of any safety control systems, such as beam blanking
- Training and competence of the operator (can be assessed by demonstration of understanding laser display operation and safety issues)
- Whether persons (and particularly the public) are at risk during installation and alignment
- The stability of the optical systems which launch both the primary and secondary beams.

It can be seen that the hazards presenting the severest outcome are not necessarily the areas focused on here. If intentional exposure of people is not planned then the whole assessment simplifies further into general safety issues with which the enforcing officer is likely to be familiar. However, if intentional exposure, such as audience scanning, is planned then a full assessment is required, as outlined in chapter 5.

The simplified approach was tested for a number of laser displays both with enforcing officers who had attended the training courses and with those who had not. Generally, the methodology was applied over the telephone to minimise the cost to the local authority. Essentially, a series of questions were presented to the enforcing officer to answer each of the bullet points above. A key issue for the enforcing officer asking the questions of the laser display company was the requirement to not appear foolish in the quality of the questions asked. This was not as much of an issue for the officers who had attended the training courses. However, for the others it was necessary to present an outline of a laser display. The hazard identification methodology provided an excellent basis for this.

The simplified methodology was also applied to a number of overseas laser displays to assist local safety officers and included the assessment of the laser displays forming part of the first annual meeting of the International Laser Display Association outside of the United States (in Canada), where audience scanning was less restrictive than in the United States. The methodology was codified as presented in figure 7.12. This recognises the importance of the assessment being carried out, at least initially, at the planning stage. Some of the changes resulting from the risk assessment may be fundamental. For example, if the venue manager wants audience scanning and the assessment shows that this is not possible with the type of laser installation, it is too late to find this out once everything has been installed. The author was involved with such a problem.

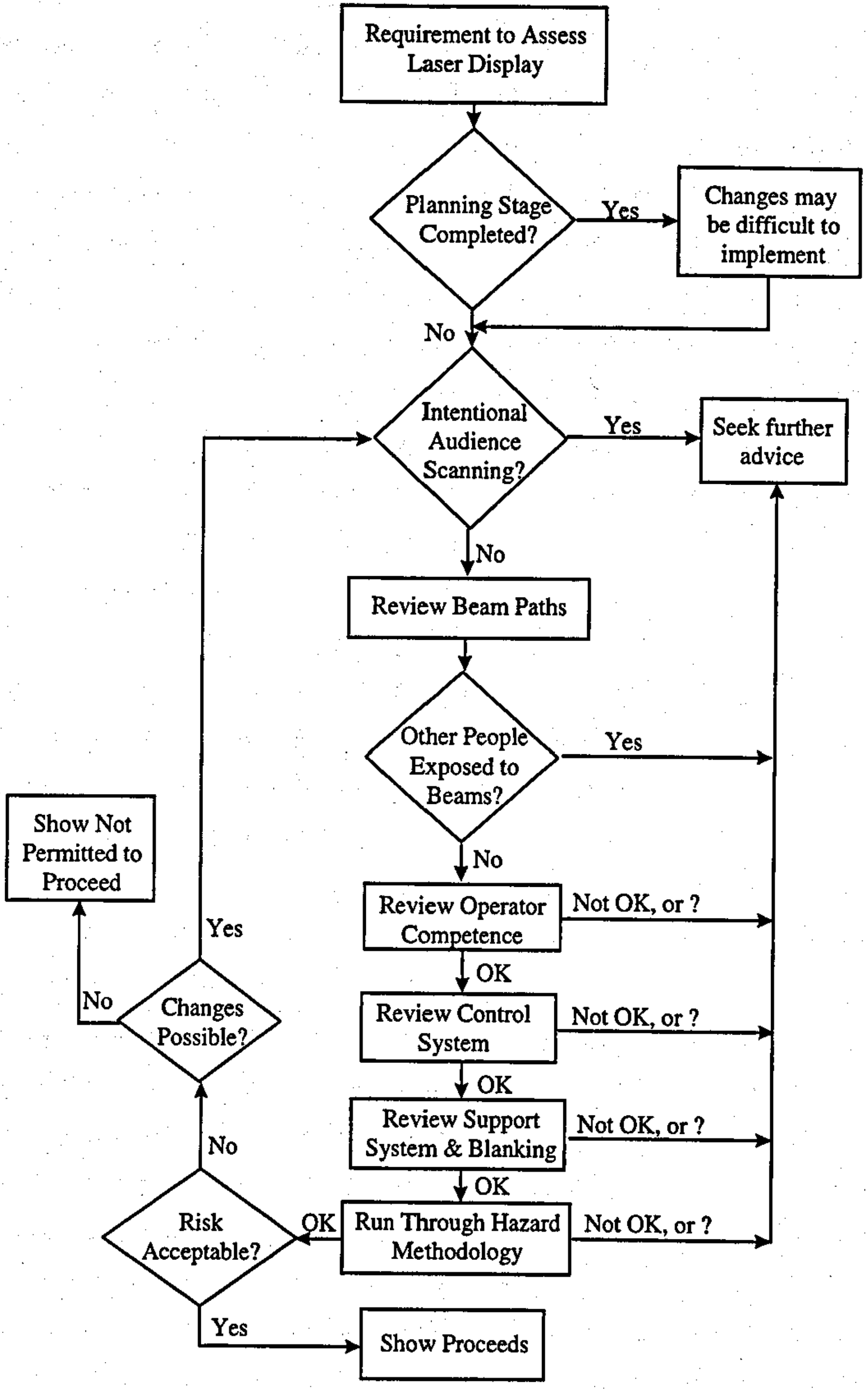
The key issue is certainly audience scanning. As has already been stressed, the assessment is not straightforward and an enforcing officer will probably need to seek further advice at this stage. If the scanning is not intended then the beam paths should be reviewed throughout the whole performance. If the display is out of doors there is the potential for persons to be exposed to the laser beams outside of the venue. Again it has been stressed that the operator competence is a major risk control measure. Careful questioning rather than formal assessment may be the only way to judge the competency of an operator. The hazard identification methodology can form a basis for a range of questions.

The control of the risk of accidental exposure, or intended exposure with un-assessed parameters, may be affected by the control system. For example, a fully automated playback system is less likely to present a risk of unplanned exposure than a fully computerised system operated manually.

A small movement in the laser display support system can result in beams moving into occupied areas, even though blanking may be used. The mechanical stability assessment should be within the capability of the enforcing officer. The stability will be an issue with temporary installations, as described in chapter 3, and also with new venues where the venue structure may be still settling. This latter point is a particular issue with some entertainment venues which use a floating construction to insulate night clubs, for example, from cinemas in multi-entertainment complexes.

The hazard assessment methodology provides a final check through all of the safety issues, to ensure that these have, at least, been considered. An acceptable conclusion from all of this would result in the risks being adequately managed and therefore the event may proceed. However, if changes are required then there will need to an element of judgement on how far back through the decision tree the assessment should re-start.

Figure 7.12 Codified Assessment Process



In all cases the methodology was found to be effective at quickly getting to the key risk management issues. It avoided wasting time on some of the detail if it was obvious that some of the key issues would prevent the show proceeding.

7.5.4 Audience Scanning Control Measures

The UK laser display industry continues to insist that audience scanning is both without risk and that is an aspect of laser displays most attractive to the customer. As such, they continue to consider methods to maintain this practice in spite of various demonstrations that they cannot provide a suitable and sufficient assessment of the risks from this practice.

Fuelled by the belief that scanning laser beams faster makes them safer, there has been some investment in audience scanning control measures which terminate the laser scan in the event of a scan-fail condition. There is also a requirement in the German draft standard for laser displays to have an automatic shut-down mechanism operating within 100 ms (DIN 1995) if audience scanning is intended.

Since the laser display companies are starting to use scan-fail control systems as a demonstration that audience scanning can be carried out safely, it is worth considering the practical implications for such devices and whether they do indeed reduce or manage the risk.

A number of scan-fail devices are commercially available and they all tend to operate with a response time from 50 to a few hundred ms. Do such products reduce the risk of intentional audience scanning? The analysis presented in chapter 5 demonstrates that the risk is not reduced by scanning the laser beam faster. Therefore, any control measure which is designed only to consider the scan speed will not be an effective control measure except to control a static beam. However, since the maximum irradiance at the audience should already be below the MPE, failure of the scanning system will mean that the MPE will only be exceeded by an order of magnitude, at most, if the beam is static.

Assuming that the scan-fail system was designed to protect from accidental entry of the laser radiation into the audience area then it is possible to calculate the time within which it would have to be effective to prevent exposure above the MPE. Since this would be an accident situation, the maximum exposure duration would be 0.25 s. The MPE for 0.25 s gives a maximum power into a 7 mm diameter aperture of 1 mW (see chapter 5). Assuming a power into a 7 mm aperture (which may be greater than the radiant power of the laser), then the time to exceed the MPE can be determined from the following. The area of a 7 mm diameter aperture is 3.85×10^{-5} m^2. The relevant MPE values are 5×10^{-3} J m^{-2} for t from 1 ns to 18 μs and 18 $t^{0.75}$ J m^{-2} from 18 μs to 10 s. Converting these into irradiances by dividing by t and into radiant power through a 7 mm aperture by multiplying by 3.85×10^{-5} m^2, this gives $1.925 \times 10^{-7}/t$ and $6.93 \times 10^{-4}\ t^{-0.25}$ W, respectively. This data is plotted in figure 5.1 and tabulated in table 7.2.

Table 7.2 Time Exceed MPE as a Function of Power into a 7 mm Aperture

Power into 7 mm Aperture (W)	Time to Exceed MPE (s)
0.001	2.33×10^{-1}
0.002	1.46×10^{-2}
0.005	3.73×10^{-4}
0.01	2.33×10^{-5}
0.02	9.63×10^{-6}
0.05	3.85×10^{-6}
0.1	1.93×10^{-6}
0.2	9.63×10^{-7}
0.5	3.85×10^{-7}
1	1.93×10^{-7}
2	9.63×10^{-8}
5	3.85×10^{-8}
10	1.93×10^{-8}
20	9.63×10^{-9}

It can be seen that using a control measure which acts within 100 ms limits the radiant power into the 7 mm aperture to about 1.24 mW. At the powers likely to be used in the entertainment industry the control measure would need to be effective in a few tens of nanoseconds. It is also important to consider what has to happen in order to control the exposure as a function of time. First the fault condition has to occur. It then has to be detected, a control measure implemented and then be effective. All of this will have to occur within the time given in table 7.2 if the beam is likely to enter areas occupied by people.

The argument above assumes that the beam is not in the occupied area when the fault condition occurs. If the fault condition occurs during intentional audience scanning then the control measure needs to be effective in an even shorter time period. Assuming that the MPE was not being exceeded during the audience scanning then the starting point for the exposure condition will not be at zero, ie the pre-existing exposure is already a percentage of the MPE.

Control systems may be used to limit the extent of the scan area, to reduce the radiant power within specific areas, or to limit the size of scan patterns. The last should also control the use of static beams in occupied areas. However, there are two main factors to consider here. The first is that the system must be set up correctly for each laser installation taking account of the layout of the venue and the laser equipment used. The second comes back to response time and table 7.2 is again important. If the control system uses software then it becomes safety critical software and should be subject to the appropriate quality assurance. The data presented in table 5.3 demonstrates the importance of using beam divergence rather than scan size to decrease the NOHD.

The conclusion from this assessment of scan-fail control measures is that they do not add significantly to the protection of persons who may be exposed to laser radiation during laser displays because the response time is not adequate using current technology. This adds weight to the argument, presented in chapter 5, that intentional exposures of personnel to laser beams can only be carried out if the static beam is below the MPE. Under these circumstances the response time of any control measure will be adequate at

100 ms. This must be achieved by increasing the divergence of the beams, or by other means, to ensure that the power entering a 7 mm diameter aperture is about 1 mW, in the absence of a detailed assessment of all of the scan patterns.

7.5.5 The Risk from Audience Scanning

The foregoing sections have highlighted that it is possible to use a simple methodology to assess a laser display if audience scanning does not take place and control measures are implemented to ensure that accidental exposures to laser radiation are unlikely. If audience scanning does take place then it is unlikely that the enforcing officers will have the necessary expertise to assess the risk directly or from information supplied by the laser company. Indeed, as has been demonstrated from this research it is also unlikely that the laser company will be able to carry out the assessment themselves.

The analyses presented in chapter 5 showed that the MPE was likely to be exceeded for most laser installations undertaking audience scanning. However, how does this translate into risk? The number of reported eye injuries is extremely low considering the number of people who have been exposed to audience scanning over the last 25 years. The survey carried out by Murphy (1995) supported the argument that the injuries are not occurring. This raises a number of issues:

- the MPE values may be wrong;
- the application of the MPE values to the exposure situation is not appropriate;
- the injuries are occurring but are not being reported, but are being attributed to something else; or
- the injuries are occuring but are not affecting the quality of vision.

The MPE values have been verified over a number of years. As shown in table 2.1, the MPE values for the visible part of the spectrum have remained constant since at least 1983. There is approximately a factor of ten between the MPE value and the ED_{50} values, where the ED_{50} is the radiant exposure required to cause an ophthalmologically significant lesion in 50% of cases (Sliney and Wolbarsht 1980). Therefore, based on this it would be reasonable to expect lesions in 50% of persons exposed at ten times the MPE. The ability of laser radiation at this order of radiant exposure to damage the retina is supported by the radiant exposure levels used in medical treatment of retinal conditions. The conclusion therefore is that the MPE values are probably correct, at least within a factor of ten. It should also be appreciated that the experimental data suggested that, even at the MPE, there was a 3% risk of a lesion.

The quantification of the laser radiation hazard in chapter 5 does make a number of assumptions, but all of these are considered to be valid for the exposure situation in the entertainment industry. If anything there are other factors which may need to be taken into account, such as compromised aversion response under the influence of drink or drugs. It could be argued that the scanned effects used in audience scanning are never stationary and even the assumption of a 0.25 s exposure is very restrictive. However, from figure 5.1 and table 7.2, it can be seen that even a single pass of a laser scan pattern is likely to exceed the MPE unless the power entering the 7 mm aperture is low. For example, the maximum power for a single 23.2 µs exposure is 10 mW. Although eye movement may be a factor for longer exposures, it is unlikely to be significant for the situation considered here.

Many laser light shows are accompanied by smoke (to make the beams visible) and possibly narcotic substances in the environment. A direct laser strike on the macula at a radiant exposure significantly in excess of the MPE is likely to result in a lesion, which is likely to result in complete loss of central, detailed vision. For this to happen, the recipient has to be looking directly at the actual or apparent source of the laser radiation. If the target site is away from the macula then the damage will be to the peripheral vision. The retina does not contain pain receptor cells and therefore any lesion is unlikely to be accompanied by pain. However, recent reports of laser pointer injuries have included references to pain. Medical assessments have suggested that the pain has come from bruising or abrading of the corneal surface by repeated rubbing of the eye with the back of the hand. Pain in the eyes may follow extended exposure to the smoke haze or other agents.

Marshall (1989) has shown that repeated lesions can be placed in the peripheral vision without the recipient being aware of them and he suggests that thousands of such lesions will not be perceived, since such damage is routinely carried out during laser treatment for some retinal conditions (Marshall 1997). This would seem to be the best argument for why more laser injuries have not been reported. This then raises a fundamental question. Is it acceptable to cause permanent damage to members of the audience, even though it does not affect their quality of life? The author's view is that it is not acceptable. Without a reasonable assessment of the irradiance levels to which persons are exposed, it is likely that higher and higher exposure levels will be used, greatly increasing the risk of more recipient observable lesions. It is also recognised that a few highly publicised incidents could trigger significant requests for eye examinations and potential litigation. This would be a global issue and not restricted to the UK.

To date, the number of reported incidents is small with 28 outdoor eye-related reports (Rockwell, 1997). The most recent injury report resulted from the use of a laser in a nightclub in Germany (Sachs et al, 1998). This followed a satisfactory safety inspection, but it is believed that the laser was replaced with one of a higher radiant power after the inspection.

7.6 Summary

This Chapter has shown how the hazard identification model can be used as input to a risk assessment for any laser display operation. It was recognised that detailed system failure assessments were generally not necessary. The process had to be reasonable and, mainly, relies on common sense.

Carrying out the risk assessment is only part of the task. The laser display industry has to prove to others, including enforcing officers, that the work it carries out is without risk to the public. A Laser Display Safety Record has been developed as a means of presenting all of the relevant information about the laser display. It is encouraging that the managers from laser display companies who have tried the format have found it useful to themselves, in addition to providing a means of informing others.

The complete Laser Display Safety Record is likely to have more information than an enforcing officer will require initially. However, a sub-set of the file can easily be provided. Such assessments should reasonably be provided for all permanent installations.

The time available to assess a laser display may be limited. Therefore, a more focused risk assessment methodology was developed to cover the key issues from any laser display by treating the display in three dimensions: compartments of the hazard identification model; persons at risk; and the life cycle. It is found that the significant risks relate to the laser radiation, although the radiation may not result in the most serious outcome. This is because, in many cases the public may be at risk and represent a large number of people at risk. The important sections of the life cycle tend to be the alignment of the laser beams and the actual performance. By following a simple methodology it is possible to identify the key issues which need to be addressed by the laser company in order to satisfy the legal requirement to undertake a suitable and sufficient assessment of the risks and to demonstrate this to an enforcing officer. If intentional exposure of people to laser radiation is not included within the show then the assessment can be straightforward and generally covers agents which are either familiar to the enforcing officer or can be easily audited such as mechanical stability, beam blanking and electrical safety. If audience scanning, for example, is an intended part of the laser display then it is either necessary to analyse each scanned effect, considering the failure conditions, or, simply, to limit the radiant power through a 7 mm aperture at the closest point of access to 1 mW. If this is measured, due account will have to be taken of the non-uniformity of many entertainment laser beam profiles: the maximum power through a 7 mm aperture will have to be determined.

Recurrent exposure of people at 1 mW is not without risk. People within the venue may be seated or at least, will not be carrying out safety critical operations. Persons outside of the venue, or who may be working within the venue, may be subject to distraction, dazzle and afterimages at exposure levels considerably below the MPE, depending on the ambient light level. If such recipients are driving or piloting vehicles then the risk could be of death and affect considerable numbers of people. For this reason, any beams which may leave the venue should also be carefully considered.

The assessment has shown that many laser shows are routinely exposing people at irradiance levels considerably in excess of the MPE values. A survey of the number of reported incidents would suggest that the practice results in a very small risk, ie a handful of incidents have been reported in the last 25 years. The small number of incident reported does not necessarily mean that injuries are not occurring: they may be in the peripheral regions of the retina where the recipient may not be aware of any degradation of vision. However, such injuries are still considered unacceptable. Quantification of the laser radiation hazard must be carried out to determine the risk from audience scanning. If the exposure levels cannot be assessed then the practice should not be permitted.

8. Relevance of the Risk Assessment Methodology to Other Laser Industries

8.1 Introduction

The research work has concentrated on developing a risk assessment methodology for the use of lasers in the entertainment industry. However, lasers are used in many other applications. Consideration is given in this chapter to how the methodology could be adapted to a number of other laser industries.

It has already been recognised (Tyrer *et al* 1994) that the generic three-component hazard identification model consisting of the laser application, delivery system and laser, could be applied to any application of laser technology. However, the detail of the hazard identification model used here, the consideration of the risks, and the presentation of the conclusions have been specific to the entertainment industry. Research, medical and industrial applications will be considered in this chapter.

There are many parallels in other industries. Each will have a life cycle, compartments of the application and zones of people at risk. The entertainment industry issues focused down on to whether the audience were exposed to the laser radiation, either by design or under reasonably foreseeable conditions. A similar methodical approach can be used to identify where the key risk issues lie in any laser application. However, a major difference is likely to be the lack of external audit and a much smaller number of people at risk.

8.2 Research

Research, by its nature, often involves the development of laser products which may not have the same level of engineered safety systems as a commercial product. However, the safety of those carrying out the work, and others who may be in the vicinity, should not be compromised.

If the research work is undertaken in an academic environment then the value of instilling a laser safety culture in students who then move on to industry should not be underestimated. However, it must also be recognised that a methodology which restricts the flexibility and effectiveness of a research programme is unlikely to be adopted at the local level.

This assessment assumes that the development of the laser product is an integral part of the research. The use of an established commercial laser product as part of a research project can be considered similarly, but the assessment will hopefully determine that the risks have been addressed by the manufacturer of the laser product.

Health and safety in research establishments in the UK, including universities, is likely to be enforced by the Health and Safety Executive. Specific laser safety guidance is available for higher education establishments (CVCP 1992) but this document is now dated and does not adequately address risk assessment issues.

8.2.1 Life Cycle

A research project will have a life cycle similar to the laser display (figure 6.1), but is more likely to have progressive developmental changes. A modified life cycle is proposed as shown in figure 8.1.

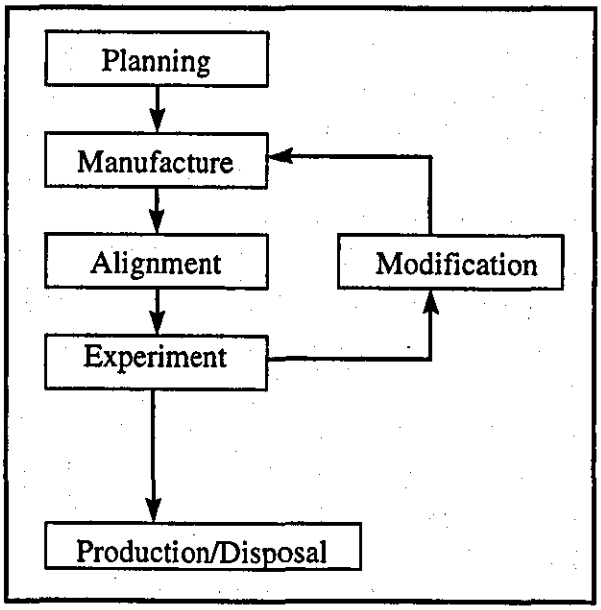


Figure 8.1 Life Cycle for a Research Project Involving an Laser

8.2.2 Hazard Identification Methodology

All of the hazard identification methodology for the display lasers (figure 6.2) is applicable, or at least should be considered. The audience could be the supervisor, or other interested parties.

The number of people at risk will generally be smaller than in laser display applications. However, special consideration should be given to staff and other people who may be in the vicinity of the research work, but not involved with it. This is particularly an issue with shared laboratories.

If the research work involves the use of a laser out-of-doors, the assessment will be even closer to the entertainment laser situation. However, it should be recognised that there is no specific requirement to involve the local authority. Special consideration should be given to the laser beam path if this is likely to present a risk to drivers of vehicles or pilots.

8.2.3 Risk Assessment

The assessment of the risks should be a systematic process making use of the hazard identification methodology, the life cycle and considering the persons at risk. Presentation of the risk assessment in a similar format to the Laser Display Safety Record would assist safety professionals within the research establishment, local managers and the person(s) undertaking the research. As the research develops, it is important to reassess the risks.

A research piece of equipment will either develop to maturity, where it is suitable for production or be dismantled at the end of the research work. Some equipment reaches maturity but remains essentially a piece of research equipment. This can mean that the risk assessment is no longer valid because the person(s) using the equipment are different to those who developed it. Their level of knowledge of laser safety issues may be much lower than the original researchers. Indeed, the equipment may be used as part of a routine process requiring little skill. Control measures, which may be tolerable during the development stage, may no longer be adequate.

8.3 Medical Laser Applications

Lasers are used in a large number of applications for diagnosis or treatment. The laser radiation is intended to irradiate people and, in many applications, cause intentional damage to human tissue.

In the UK, the only specific legal control of the use of medical lasers is in certain private practices under the Nursing Homes and Mental Nursing Homes Regulations 1984 (HMSO 1984a) which were made under the Registered Homes Act 1984 (HMSO 1984b). Regulation 3 of the Regulations specifies class 3B and class 4 lasers as being subject to control for the purposes of the Act. Generally, it will be staff from the local health authority who will be required to assess the laser safety in the private practice. Therefore, the methodology developed for laser safety in the entertainment industry is likely to be particularly relevant to this application.

The use of lasers in hospitals forming part of the National Health Service is subject to the general requirements of the Health and Safety at Work Act 1974 (HMSO 1974) and the Regulations made under that Act. Auditing of laser safety in healthcare facilities is likely to be a function of an in-house radiation protection professional who has some expertise in laser safety. Enforcement of the safety legislation will be the responsibility of the Health and Safety Executive with the Department of Health overseeing medical practice. The Medical Devices Agency (MDA) have a rôle in the safety of equipment used in medical practice, including medical lasers. The MDA have produced guidance on the safe use of lasers in medical and dental practice (MDA 1995). This guidance provides little practical advice on assessing risks in compliance with general safety legislation but it does address a number of practical laser safety issues.

One area of laser treatment that appears to fall outside of the scope of either being a private medical practice or a National Health Service facility is beauty treatment. In particular, lasers are being used for the removal of body hair. The general laser safety can be addressed, and enforced, by local authority environmental health officers, but the clinical direction of the treatment, including assessment of competence is not clear. The practical application of the risk assessment methodology presented here should ensure that the safety issues are addressed irrespective of who enforces health and safety, and other, legislation.

8.3.1 Life Cycle

The life cycle considered here is that which effects the healthcare facility. The development of the laser, its manufacture and transport to the healthcare facility are not considered.

The life cycle within a healthcare facility is different from an entertainment laser because it also has to take account of different users and different applications of the same equipment. An outline of a suggested life cycle is presented in figure 8.2.

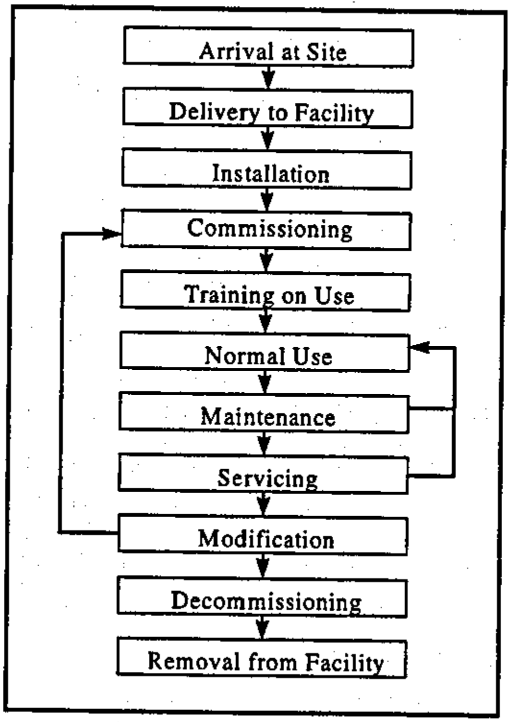


Figure 8.2 Life Cycle for a Medical Laser

8.3.2 Hazard Identification Methodology

The hazard identification methodology for entertainment lasers can be modified for medical laser applications. The audience can now be replace by the patient. The operator may be one person or it may be two. In many surgical operations, the surgeon will be termed the laser user, ie the person who presses the pedal that fires the laser at the target. The person who sets the laser parameters may be a support nurse operating under the instruction of the surgeon. This nurse will put the laser into the "ready" mode, essentially giving the surgeon the ability to fire the laser.

As part of the consideration of the beam paths, the laser process will have to be considered, bringing the model in line with the original model developed by Tyrer *et al* (1994). Since surgical applications cause damage to human tissue, which may be diseased, it is important to consider the resultant fume.

Hazards may be accessible during some parts of the life cycle and not others. For example, work carried out during commissioning, servicing and modification may involve the side panels of the laser being removed and the laser operated with interlocks overridden. Apart from the laser radiation hazard, collateral radiation and high voltages may be accessible.

8.3.3 Risk Assessment

There are several reasons why the risk assessment is important in a healthcare facility. Many such facilities have a number of risks and are generally operating under strict financial constraints. The risk assessments provides input to a cost-benefit exercise which balances all of the risks associated with the work in the healthcare facility.

The control measures in place during different parts of the life cycle may not be adequate for all persons potentially at risk. For example, during servicing operations the engineer, who may be a contractor from the laser supplier, may use adequate control measures to protect themselves (wear laser safety goggles) but not consider other people in the vicinity. The risk assessment from the laser supplier should address this, or the issue should be addressed by the healthcare facility.

Many healthcare facilities are large with multiple laser applications. Presentation of the risk assessment and other information in a formal record similar to the Laser Display Safety Record summarises the status of laser safety. Unlike many laser display installations, the record will be relatively static, although it is important that it is reviewed periodically and when circumstances change. This can include the purchase of new equipment, re-siting of existing equipment, new medical procedures or the transfer of physical direction of the process to another group of staff. An example of the latter is where a nurse undertakes tattoo removal or the treatment of benign vascular lesions under the clinical direction of a physician.

The use of a formal Record is also useful for demonstration of regulatory compliance, including compliance with the Registered Homes Act (HMSO 1984b). The officer assessing a private healthcare facility for registration under the Act will be able to judge the laser safety infrastructure and risk assessments on the basis of information already recorded rather than having to seek the information by interview.

The risk assessment methodology described here, and written by the author, has been incorporated in Annex C of a draft International Electrotechnical Commission report on medical laser safety to be published as part 8 in the IEC 60825-X series (IEC 1998).

8.4 Industry

The use of lasers in industry is widespread with applications varying from manufacture to quality assurance. The objective should be to ensure that personnel are not exposed to the laser radiation and other hazards associated with the use of the laser. Lasers in industry may be used by people who have no awareness of laser safety issues, and ideally, should have no need to understand the laser safety issues if these are addressed satisfactorily during the design and manufacture stages.

8.4.1 Life Cycle

The life cycle for a laser product used in industry may include the life cycle for a research application. However, it is assumed here that the life cycle commences with the customer identifying a need for a piece of equipment. The manufacture and supply of the equipment is not considered.

The life cycle is identical to that for the medical laser (figure 8.2). In some applications, such as materials processing, the different tasks undertaken by the laser product may present different safety issues.

8.4.2 Hazard Identification Methodology

Ideally, laser radiation will be less of a safety issue with industrial laser products. However, the hazard identification methodology for entertainment lasers can still be adapted for these applications. As with the medical lasers, the laser process may be more important than the beam path. A suggested hazard identification methodology is presented in figure 8.3.

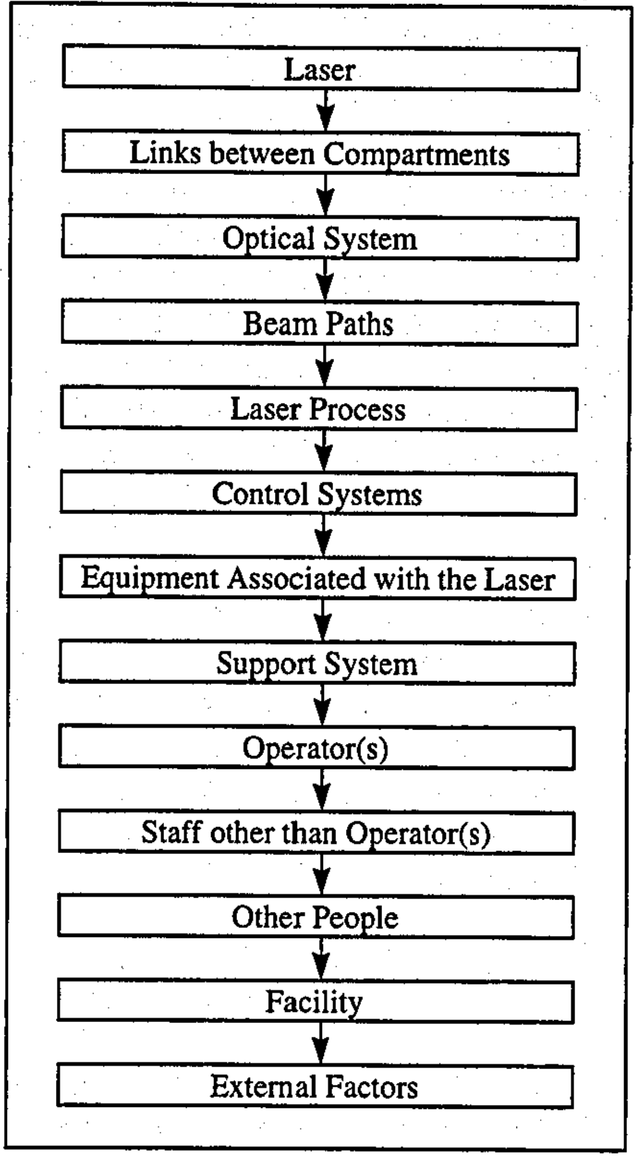


Figure 8.3 Industrial Laser Hazard Methodology

The number of people at risk from industrial applications is generally small and will usually be restricted to employees or contractors working on the laser product. However, consideration should also be given to visitors and to employees who may be at particular risk through ignorance, such as recent recruits and cleaning staff.

8.4.3 Risk Assessment

Risk assessment should be a routine activity for many companies using lasers in industry. The use of the hazard identification methodology and following this through to the risk assessment for the laser application should form part of the company's overall risk assessment.

The risk assessment, and the other information relating to laser safety, could be presented in a ring binder file similar to the Laser Display Safety Record, although it is more appropriate to call this a Laser Safety Operational File. This format has been used by the author for a number of industrial applications.

8.5 Summary

The hazard identification and risk assessment methodology were developed initially for the entertainment industry. However, the methodology can be adapted to a number of different laser applications. Indeed, the structured approach can be applied to any application.

It is recognised that some applications will require a more formal approach to failure analysis and risk assessment but these generally apply at the design and manufacture stage. By the time a product reaches the user, most of the safety issues should have been considered and addressed. The requirement to undertake a risk assessment remains under UK law. It is compliance with this requirement that the methodology described in this chapter should help to address.

9. Conclusions and Recommendations for Further Work

9.1 Introduction

The analysis of available guidance and text books relating to laser safety suggested that laser radiation issues were well understood (chapter 2). Therefore, the main issues initially covered by this research work were the non-radiation safety concerns. However, an analysis of several laser display events (chapter 3) suggested that laser radiation was still an issue. There was also a gulf between laser display companies and enforcing officers. This was believed to be due to a lack of understanding of each other's standpoint. The author's experience of dealing with enforcement officers, and the acceptance of NRPB by these organisations meant that liaison would be straightforward. Such collaboration with the laser display companies would have to be earned through mutual respect and understanding.

A survey of the understanding of laser safety within local authorities was well supported (chapter 4) and reinforced the impression that local authorities did not necessarily have specific expertise for assessing the safety of laser displays. Similar surveys of the laser community produced a disappointing response, suggesting suspicion of 'officialdom'. However some data was acquired from the laser display companies during a seminar held at NRPB.

It was necessary to gain a thorough understanding of the technology, techniques and day-to-day problems of putting on a laser display event. This required co-operation from a number of laser display companies who were prepared to spare time to be questioned and observed.

It was recognised that training and information were important to ensure that all parties understood each other's points of view and specific problems. To meet this need a number of joint NRPB/Loughborough University training courses were run specifically aimed at laser safety in the entertainment industry. These courses also helped to provide feedback on the main issues. However, they also demonstrated that the techniques developed at that stage were not giving the enforcement officers the confidence they needed to assess laser displays without further assistance. This was despite many of the safety issues being within their expertise. Therefore, it was necessary to modify the techniques developed into a risk assessment methodology which focused on the key risk issues and the people at greatest risk.

Audience scanning remained a key issue and one which, by measurement and theoretical assessment, appears to put the public at considerable risk of eye injury. However, this risk is not supported by reported incidents suggesting that the practice may not present as great a risk as predicted or that the number of eye lesions is significantly under-reported. The latter is thought to be the case.

9.2 Conclusions

A number of key issues have been resolved as a result of this research and it is strongly believed that the risk from the use of lasers in the entertainment industry can be managed successfully at least in part, by implementing the risk assessment methodology developed. The approach has been to solve a practical risk assessment issue, rather than a strict theoretical determination of the risks from the use of lasers in this industry.

The situation at the start of the research was as follows:

- laser display companies were not routinely assessing the risks from their work activities;
- laser display companies complained about inconsistent enforcement between enforcement officers;
- the enforcing officers found the laser display companies less than helpful and unable to convince them of any risk management considerations;
- the enforcing officers believed they had little understanding of the technology, methods of generating laser effects, or the safety issues;
- the current practice by the laser display companies was less than professional, even when viewed from within the entertainment industry;

- audience scanning with laser beams was routinely taking place with no quantification of the hazard;
- there was a lot of folk lore about the safety of laser beams, such as beams being safe after reflection from a mirror, irrespective of incident power, and audience scanning is safe provided the beams are scanned fast;
- the laser display companies did not have a complete understanding of the technology they were using, including the scan speeds used;
- consultants were providing advice with little understanding of the key laser safety issues, adding to the impression that there were few safety issues.

Laser displays were routinely being assessed based on limited information provided on a proforma included as appendix 3 to the then UK laser display guidance, PM19 (HSE 1980). These proformas rarely related to the venue or the laser display equipment used and most enforcing officer either accepted them at face value or admitted they did not understand them. A major factor in the problem developing as far as it did was that the laser display companies and the enforcing officers did not communicate with each other and, probably did not trust each other.

The development of assessment tools has relied on breaking down the barriers between the laser display companies and the enforcing officers and attempting to build a bridge between the two. Therefore, the tools have needed to be useful to both parties and, as a result of this should also be useful to others, such as the venue management and event promoters.

In parallel with the development of the assessment tools has been the need to understand the technology used, the artistic techniques for producing laser shows, the problems of physically staging a laser show and the enforcement issues. In essence, it was necessary to work alongside laser display companies and see the world from their viewpoint, and also to work with the enforcing officers.

The development of the assessment tools has been an iterative process which has involved a number of hypotheses, testing those hypotheses and feeding the results back to new, further developed hypotheses. Existing guidance from the literature and laser safety standards suggested that laser radiation issues were well understood, but little practical guidance was available for identifying the non-laser-radiation issues. Therefore, the first tool developed was a checklist, termed SCALE DOVES. This was an attempt to structure the areas where the hazards may exist. The major success of this initial checklist was the identification of the problem of assessing laser radiation since intended audience scanning with laser beams was widespread. There was also some confusion with the checklist about what was a hazard and who was at risk from the hazard.

A hazard identification methodology was developed which used a logical path from the laser to the audience, the venue and outside. Hazards could be identified for each of a series of compartments of the laser display. The life cycle of the display was also identified as important. Planning, the first stage, was critical, but there were a number of stages and the hazards for each of the compartments could be different at each stage of the life cycle. It was also recognised that different people could be at risk from the different hazards in the different compartments at different stages of the life cycle.

The information that could now be collected for a laser display event was significant, or at least guidance was structured on the questions to ask. Presenting the information to the enforcing officer was now an issue. A Laser Display Safety Record was developed as a structured means of presenting the information and this approach was tested by a number of laser display companies for a number of events. Two key issues arose: the volume of paperwork required (with the amount of time and effort required to produce it); and the time necessary to assess it. On the positive side, the promoters and venue managers were very keen on the approach since it was a means of demonstrating a professional approach to the laser performance. Safety, they assumed would follow from that.

When considering the three variables for the risk assessment methodology: the compartments of the laser display; the life cycle; and the people at risk, it was apparent that the key risk issues occurred at specific regions of combination of the three variables. Although the laser display company staff and others in the immediate vicinity of their work may be at risk of death from their work, the audience generally were not. However, the number of people in the audience is generally much greater than the number of employees at an entertainment event. To maximise the effectiveness of a risk assessment, ie to implement effective risk management, it was important to consider the greatest number of people at risk, especially as a reasonably foreseeable outcome could be a serious eye injury. Such an outcome has the potential to significantly effect the quality of life of the persons at risk. Quantification of the laser radiation hazard during intended audience scanning suggested that the maximum permissible exposure (MPE) levels were being exceeded for situations where the power through a 7 mm diameter was more than about a factor of ten greater than the MPE for a static beam, ie 10 mW.

The risk assessment methodology was focused to take account of the key risk issues since time was generally a major issue, certainly for any enforcing officer required to review the risk assessment provided by a laser display company. Specific sections of the three-dimensional risk assessment methodology were taken which primarily considered the public: the alignment and performance stages of the life cycle; the laser beam paths, operator competence, control system and support system compartments; and the audience and other members of the public persons-at-risk zones.

The methodology could now be condensed into a flow chart for the enforcing officer to decide whether they have the necessary expertise to assess the safety of the laser display. The key issue will be whether audience scanning is an intended or reasonably foreseeable part of the laser show. If it is not, the assessment simplifies to a number of issues which the enforcing officer is likely to have experience of, such as the risk from mechanical and electrical hazards. If laser beams are an issue, or satisfactory conclusions cannot be drawn from the management of the risks from the identified hazards then the enforcing officer has a number of options: seek further advice on assessment of the risks; request further information to be able to make a judgment; or prohibit all or part of the performance.

Although the condensed methodology permits a reasonable assessment of the key risk issues, it will still be necessary to consider the remaining elements of the hazard identification methodology, even if these are not considered in detail.

One of the main control measures for many of the risks associated with the use of lasers in the entertainment industry is the competence of the operator(s). There is no nationally recognised training programme for laser display operators, although there is an initiative to develop such training generally for the entertainment industry by Loughborough College in the UK. This is intended to include laser display operators.

There is one remaining problem with the application of the methodology. It should certainly assist enforcing officers. A small number of laser display companies have also seen the benefits, including a number from outside the UK. However, the whole methodology is based on a requirement to convince someone else that the risks from the laser display have been adequately managed - the driving force for preparing the assessment is that the show may not take place if the assessment is not undertaken. However, many laser displays taking place in the UK will not be subject to entertainment licensing. As such, unless there is a culture change within the industry, or promoters and venue manager insist on reviewing risk assessments, these are unlikely to be completed for these other events. Adoption of the methodology resulting from this research should go a significant way towards ensuring that a consistent approach to determining the risks and how the assessment should be audited exists throughout the UK, if not the world.

There was a great deal of confusion amongst the laser display companies on the legislation that applied to the use of lasers in the entertainment industry and the status of published guidelines. These issues have been addressed in chapter 2. It will always be better for the laser company to approach the local authority to determine if they wished to be involved with an assessment of the laser safety issues than to find out that the enforcing officer stops the laser show on the night because they were not informed and should have been.

It had been hoped that the formation of the Entertainment Laser Association would provide an impetus for the industry to dispel its image of being less than professional and work towards self-regulation. This has not proved to be the case. The industry in the UK hangs on to the belief that their industry is safe and that audience scanning is necessary and without risk. This is based purely on the lack of reported injuries and not on any practical assessments. This attitude is in marked contrast to the international situation. The International Laser Display Association (ILDA) has taken this research very seriously and joint measurements have been carried out to confirm some of the basic premisses, such as the maximum irradiance that can be put into an audience, and that higher scan speeds do not make beams safer. It is also the intention of the ILDA Board of Directors to produce an international safety guide produced by the industry, which takes account of the methodologies and conclusions of this research.

Many of the UK laser display companies seem to consider that audience scanning is the most important part of the show. However, this view is generally not shared by the audience. Certainly, close proximity to laser beams is exciting and impressive but repeated scanning across the eyes, even at irradiance levels close to the MPE triggers the blink reflex. Whilst this may be acceptable a couple of times during a performance, it is annoying if it happens persistently. Observations of audiences during audience scanning clearly shows how they anticipate the scan approaching them and take evasive action after a while. One of the performances assessed during this research consisted of multiple diffraction beams passing through the audience area. The effect was generated by passing the primary beam through one rotating diffraction grating and then passing the diffracted pattern through a second diffraction grating rotating in the opposite direction. The zero order was dumped in an inaccessible area. The accessible diffracted beams were measured by the laser display company with the power to the motor drives disconnected and the maximum power into a 7 mm aperture was confirmed as about 0.07 mW from an input power of 5 W. The beams were visibly bright enough to produce a very impressive effect - the audience were essentially bathed in a mass of light rays of different colours. However, the visual stimulus was such that the beams could be viewed without blinking. This demonstrated that audience scanning effects could be used below the MPE, and indeed at a level which would not trigger the eye's aversion response, and still remain impressive.

For laser display companies who have built up their experience with audience scanning effects it is difficult to move away from such effects. This is likely to be due to the greater artistic input required to generate impressive effects without the "easy" option of scanning high power beams through the audience. It is interesting that the US laser companies have developed far more impressive graphical shows since audience scanning has generally not been an option for them. There will need to be an investment in the capabilities of the laser radiation as an artistic medium. Some companies are combining laser radiation with other media, such as video projection (Ward 1998).

The development of the risk assessment methodology has identified the benefit of a structured approach. The methodology, taking account of the three dimensions of the input parameters can be applied to other laser applications. As has been demonstrated in chapter 8, the methodology is equally applicable to applications where there are open beams, such as medical applications, and possibly research, and to industrial applications where the laser product is used as a tool, by employees who may need to know nothing about the laser inside the product. In these applications, the culture of health and safety is likely to be further developed than in the laser display industry. However, it is still likely that the laser application will be seen as something different and very complicated to assess. The actual risks may be difficult to quantify in some applications where the technology is still being developed, such as fumes from materials processing.

In summary, the situation at the conclusion of this research work is as follows:

- many laser display companies have accepted the need to assess the risks from their work;
- laser display companies have started to appreciate the views and responsibilities of enforcing officers;
- enforcing officers have developed a greater understanding of the issues associated with staging laser displays;
- the legal situation concerning laser displays has been clarified, mainly for the laser companies, promoters and venue managers;
- all parties have gained a greater understanding of the technology used in laser

displays and means of assessing actual performances;

- a methodology has been developed which guides laser companies through the risk assessment process and a means of presenting the conclusions has been demonstrated;
- taking due account of the time taken to undertake a full risk assessment, criteria have been developed to focus the effort on the key risk issues;
- the problems of pre-existing measurement methods for quantifying the laser radiation hazard have been highlighted;
- new measurement methods have been developed for quantifying the laser radiation hazard, especially during the intentional scanning of the audience;
- audience scanning does not take place at venues where the author is involved with laser safety, except under well defined conditions of operation;
- the complete quantification assessment of a show which includes intentional audience scanning is very time consuming and is generally still beyond the capability of the laser display companies;
- in general, a measurement of the static laser beam at the closest position of the audience, and comparison of the measured value with the maximum permissible exposure, gives a good indication of the acceptability of such a beam scanned across the audience;
- a flow chart to assist enforcing officers with assessing laser displays has been introduced;
- where audience scanning does not take place, the safety assessment is well within the capability of most enforcing officers;
- the results of the research have been accepted by the International Laser Display Association and are being taken into account in proposed industry-prepared international guidance;
- much of the methodology for assessing laser displays is applicable to other laser applications.

9.3 Suggestions for Further Work

The risk assessment methodology is mature and has been used on a number of occasions by a number of different people. As stated above, it will only become adopted by the laser display industry if they can see the benefits to them, and these will normally be commercial benefits. Adoption by enforcing officers should ensure a consistent approach across the UK. The methodology could be programmed into a decision support system which would be of value to the laser display company, the enforcing officers, venue managers and the promoters. It is important that the methodology does not become a "worked example", which is copied for different performances without consideration of the performance and/or venue specific issues.

The software developed for this application could be tailored to specific industries or could be generic. Such an approach may be able to attract financial support from government departments or regulators.

The existing guidance for the safe use of lasers in the entertainment industry throughout the world has generally been written by enforcing bodies and not by persons within the industry. The initiative by the International Laser Display Association to develop its own international guidance is to be welcomed. The research undertaken here will hopefully be taken forward by the industry under the ILDA banner to provide detailed practical guidance on how to undertake safe laser shows, the technology required to ensure that they remain safe, and that the residual risks can be assessed.

The development of engineering solutions to the control of audience scanning will be welcomed. There should be commercial advantages to such developments but they must take account of the actual exposure situations likely to be encountered. If the judgment of the operator can be removed then the performance should be more controlled. However, as has been seen in chapter 7 with some scan-fail detection products, the philosophy behind any control measure must be sound.

There needs to be a major investment by the industry either as individual companies or collectively to consider what makes an impressive laser show. The ability to arbitrarily scan laser beams in to audience areas for effect has stifled the development of more impressive beam effects. Audience scanning generally appears effective to a small proportion of the audience at a time, and these people are spending a significant amount of time recovering from eye exposures, even at irradiance levels below the MPE. Beams projected just out of reach above the audience should present the same impact to a much larger proportion of the audience at a time. Laser show can be impressive and the risks can be effectively managed. Hopefully, future research will not include studies of eye injuries resulting from the use of lasers in this industry.

10. Publications

The following papers and articles have been published during the course of this research work.

Non-ionising Radiation - Lasers
J B O'Hagan
IN Proceedings of the Environmental Health Congress, Harrogate 15-18 September 1998. Chartered Institute of Environmental Health, London

Laser Pointers
J B O'Hagan and R Hill
Radiological Protection Bulletin, No. 199, pp15-20, March 1998

Laser Pointers
J B O'Hagan and R Hill
NPRB Information Services Leaflet 1/98 30 January 1998

Lasers. Chapter in Croner Laboratory Safety Manager.
J B O'Hagan
Approved and Submitted January 1998

Reply to Letter to the Editor
Lasers in Places of Public Entertainment
J B O'Hagan, D A Corder and J R Tyrer
Journal of Radiological Protection, 18, 2, 139-140, 1998

Safety Assessments of Visible Scanned Laser Beams
D Corder, J B O'Hagan and J R Tyrer
Journal of Radiological Protection, 17, 4, 231-238, 1997

Safety Aspects of Laser Displays
J B O'Hagan
Radiation Protection Dosimetry 72, 3-4, 241-248, 1997

The Role of the Laser Safety Adviser in Regulatory Compliance
J B O'Hagan and R Hill
Published in the Proceedings of the International Laser Safety Conference 1997, Orlando, Florida, USA

Assessing Laser Safety in the Entertainment Industry: A systematic Approach
J B O'Hagan and J R Tyrer
Published in the Proceedings of the International Laser Safety Conference 1997, Orlando, Florida, USA

The Influence of Training and Education on the Perception of Laser Safety
E Raymond, J R Tyrer, J B O'Hagan and R Hill
Published in the Proceedings of the International Laser Safety Conference 1997, Orlando, Florida, USA

A Practical Approach to Laser Risk Assessment
J R Tyrer, E Raymond, L H Vassie and J B O'Hagan
Published in the Proceedings of the International Laser Safety Conference 1997, Orlando, Florida, USA

Scanning with Safety
J B O'Hagan
Disco Mirror, pp 34-35, November 1996.

Laser Queries
Comment on "Laser Misunderstandings"
J B O'Hagan
Letter to the Editor of Health and Safety Practitioner. Published in 14, 3, March 1996

Laser Safety in the Entertainment Industry
J B O'Hagan
Radiological Protection Bulletin, No. 173, pp 21-23, January 1996

Book Review of "Laser and Eye Safety in the Laboratory" L Matthews and G Garcia, IEEE Press (1995)
J B O'Hagan
Radiological Protection Bulletin, No. 173, pp 23-24, February 1996

Laser Safety - Where are we going?
J B O'Hagan, D Corder, E Raymond, J R Tyrer
Disco International, 226, 44-46, December 1995

Comment on "Safe Use of Lasers"
J B O'Hagan
Letter to the Editor of Health and Safety Practitioner. Published in 13, 10, October 1995

Creating a Laser Spectacle with Safety
J B O'Hagan
Event Organiser No. 22, 12-13, October 1995

Laser Safety Basics
J B O'Hagan
Presented at Laser F/X: The Light Show Conference, Burlington, Ontario, Canada 8 May 1995

A Practical Approach to Risk Assessment in the Laser Entertainment Industry
J B O'Hagan, E Raymond, J R Tyrer
International Laser Safety Seminar, Vienna, May 1995 (presented by JRT)

Some Safety Issues from the Use of Lasers in the Entertainment Industry

J B O'Hagan

Health Safety and Welfare at Pop Concerts and Similar Events Seminars, Easingwold

17 November 1994, 8 December 1994, 28 February 1995 and 23 March 1995

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Appendix A

Details of Laser Display Systems

A.1 Introduction

This appendix reviews some of the laser display systems used in more detail than chapter 3 and is based on discussions with a number of laser companies. Although there was a belief that they all had unique systems, they were all very similar in concept, if not in detail. The appendix starts with the types of lasers known to have been used in laser displays. Then the optical systems are introduced, both in terms of the processing close to the laser and in the display environment. Finally, the control systems are introduced.

A.2 Lasers

There are a great many types of lasers commercially available. This section describes only those lasers known to have been used for mainstream entertainment applications. It is possible that other lasers have been used, especially in research environments.

A.2.1 Helium-neon Laser

The helium-neon (He-Ne) is the most popular of the so-called gas lasers, representing 64% of the units sold in the UK in the early 1990s (Vassie et al 1993). The most common wavelength is 632.8 nm which is red. However, units are also available which emit at other visible wavelengths - 543.5 nm (green); 594.1 nm (yellow); 604 nm (orange); 611.9 nm (orange) and 640.1 nm (red).

The 632.8 nm laser is available at radiant powers up to about 75 mW. Radiation at other wavelengths is produced less efficiently and therefore the maximum radiant powers may be only a few milliwatts. However, the response of the eye at each wavelength also needs to be taken into account. This response depends on the level of light as well as wavelength: at high light levels this is the photopic response (peak at 555 nm - see figure

3.2); at low light levels this is the scotopic response (peak at 510 nm). The shift in the peak response wavelength is the Purkinje Effect (Longhurst 1973). The reason for the shift is the different receptors in the eye. Cones, are most densely located in the central fovea, a small depression in the centre of the macula lutea. These cones are responsible for colour vision and the sharpness of vision in bright light. It is thought that there are three different types of cones which each have their own relative response as a function of wavelength, peaking in the red, green and blue parts of the electromagnetic spectrum. Colour is determined from the differential output of the three types of cone (Tortora and Anagnostakos 1990). The rods are located away from the macula lutea in the remainder of the nervous retina. These respond to low light levels and produce an essentially black and white image. The rods are good for identifying shapes, shades of light and dark, and movement.

The relative photopic and scotopic responses for the He-Ne visible wavelengths are presented in table A.1 along with the radiant power required to produce the same perceived brightness as from a 1 mW 632.8 nm He-Ne laser. In most situations the photopic response will dominate, even though the ambient light levels may be low. As explained in chapter 5, the damage response of the eye is taken to be independent of wavelength from 400 nm to 700 nm for exposure times up to 10 s. Therefore, if the colour of the radiation is not important a green He-Ne is preferable to, for example, a red He-Ne.

Table A.1 Comparison of Photopic and Scotopic Eye Responses to He-Ne visible laser wavelengths

Wavelength (nm)	Photopic Response (Relative to Peak Response at 555 nm)	Radiant Power (mW) to Stimulate the Same 'Brightness' as 1 mW at 632.8 nm Assuming Photopic Response	Scotopic Response (Relative to Peak Response at 510 nm)
543.5	0.95	0.25	0.67
594.1	0.75	0.32	0.08
604	0.60	0.40	0.05
611.9	0.48	0.50	0.04
632.8	0.24	1.00	<0.01
640.1	0.17	1.41	<0.01

The divergence of the He-Ne laser will depend on the cavity length and can range from 8 milliradians for a short laser down to about 0.5 milliradians for a long, high powered model (Hecht 1992). Exit beam diameters are of the order of 1 to 2 mm.

He-Ne lasers are available as single units or as separate laser heads and power supplies. The laser pumping is produced by a discharge in the laser tube, which contains a mixture of helium and neon gas (usually in the ratio 5 - 12 to 1). An initial ignition voltage of 10 kV is required and thereafter 1 - 2 kV at a few milliamperes. Although it is possible to purchase low power (about a milliwatt) lasers which are battery powered, most require a standard mains supply (230 V).

Cooling is provided by passive air cooling although forced air cooling may be used for higher radiant power devices. The efficiency is in the range of 0.01 to 0.1 percent. Therefore, a 75 mW laser would be expected to produce from 75 to 750 W of heat.

The main hazard from a He-Ne laser is the laser radiation. However, the high voltage presents an electric shock hazard if the casing is open. It is also possible to receive a shock from the connector to the laser tube in separate units if the connector is removed before the charge on the laser tube has decayed.

He-Ne lasers are generally used for small venues, where the complete laser display system is enclosed in a single cabinet. However, they can also be used, for example, in pantomimes as a dancing light such as Tinkerbell in Peter Pan. Here colour is important. Although green light would be ideal from the perspective of maximum brightness for a given power, this colour represents bad or evil. Therefore, a compromise of orange has been used.

A.2.2 Argon-ion laser

The argon-ion (Ar-ion) laser comes from a family of noble gas ion lasers. It has been the mainstay of the medium-to-large laser display systems since the beginning. The principal wavelength depends on the construction of the laser. Low radiant power air-cooled Ar-ion lasers tend to have a predominant emission at 488.0 nm (blue) with an additional emission at 514.5 nm (green). However, the larger water-cooled lasers tend to predominate at 514.5 nm. Most Ar-ion lasers used in display applications make use of both the 488.0 nm and the 514.5 nm emissions. The quoted radiant power of commercial Ar-ion lasers generally includes the total radiant power at both wavelengths. There are also a number of minor wavelengths from the Ar-ion laser. The two of interest for display purposes are 476.5 nm and 457.9 nm, both in the blue part of the electromagnetic spectrum.

Ar-ion lasers can range in radiant power from a few milliwatts to about 50 W. Air cooled lasers up to about 100 mW are used in indoor venues. Water-cooled lasers up to 20 W have been used for outdoor events although the typical unit is 3 - 5 W. The beam divergence is typically in the range 0.4 to 1.2 milliradians with an exit beam diameter in the range 0.6 to 2 mm (Hecht 1992).

The Ar-ion laser is excited by a high-current discharge that passes along the length of the laser tube. An initial spike of a few thousand volts breaks down the gas, then the voltage drops to between 90 and 400 V, while the current increases to between 10 and 70 A. High current densities in the centre of the laser tube provide the energy that both ionises the argon atoms and provides the pumping to the upper excited states.

Cooling is provided by forced air or by water. The power supplies of multi-watt lasers may also require cooling. The efficiency of Ar-ion lasers is between 0.001 and 0.2 percent and will be lower for lasers emitting a single wavelength as opposed to both primary wavelengths. Quoted electrical inputs are 8 to 26 kW for a typical 3 to 5 W multiline output (Hecht 1992).

Air-cooled lasers up to about 100 mW can be powered from a standard 230 V supply. Higher radiant powers will require a three-phase supply at 415 V.

A typical Ar-ion laser will consist of several components, most of which are heavy. A small air-cooled laser may consist of a power supply, a control module and the laser head, where the latter contains integral cooling fans. Higher radiant power lasers will consist of a power supply (which may require input from a three-phase generator, especially if used out-of-doors), a control module (possibly with a remote radiant power/current control), laser head, cooling water pump and cooling water supply, which may be direct from a mains supply or may be from a storage tank. The water may also be passed through a cooling plant.

A 20 W laser head alone may weigh 100 kg and be 2 m long with a cross section of 0.2 m by 0.2 m. An important consideration for peripatetic laser display work is the ability to safely move, install and dismantle the laser system. The mixture of high voltages (at high currents) and water is potentially hazardous.

As described in section A.2.1, the cones on the retina, which give the perception of colour, are believed to have peak responses in the red, green and blue parts of the electromagnetic spectrum. Therefore, combining a He-Ne laser operating at 632.8 nm with the green and blue emissions from an argon laser should provide a white light source. From the data plotted in figure 3.2, the ratio of the radiant powers would have to be 1:0.34:0.93 for 632.8, 514.5 and 488.0 nm, respectively. Since the maximum radiant power from a He-Ne laser is about 70 mW, this means that the maximum power in the 514.5 nm line is restricted to 24 mW and 65 mW for the 488.0 nm line. This can be achieved easily using an air-cooled argon laser, but the absolute brightness will only be sufficient for small venues.

A.2.3 Krypton-ion Laser

The operation of the krypton-ion (Kr-ion) laser is similar to the argon-ion described in section A.2.2. However, this laser has a strong emission at 647.1 nm (red). There are also emissions at a number of other wavelengths, principally 406.7 nm (violet), 413.1 nm (violet), 468.0 nm (blue), 530.9 nm (green), 568.2 nm (yellow) and 676.4 nm (red).

The Kr-ion laser is less efficient than the Ar-ion laser, requiring about ten times more electrical power for the same radiant power. Most Kr-ion lasers are therefore water-cooled. Typical lasers used in the entertainment industry have a maximum radiant power of less than 1 W.

A.2.4 Mixed Gas Lasers

Mixed gas or white light lasers have a combination of krypton and argon in order to produce a range of wavelengths. It is possible to generate any colour from a combination of red, green and blue light. Therefore, the emissions from a laser generating these three colours can, in theory, be combined to produce any colour, including white light. Originally, the 488.0 nm and the 514.5 nm emissions from the Ar-ion laser were combined with 647.1 nm emission from Kr-ion. However, the addition of these wavelengths could not generate a brilliant white light. The next stage was to include the 568.2 nm emission to add some yellow. Modern white light lasers aimed at the entertainment industry are quoted as emitting radiation at eight wavelengths. These are stated in table A.2, along with the ion source and the relative radiant power for a modern commercial laser (Cambridge Lasers 1994).

Table A.2 Emission Wavelengths from a Commercial White Light Laser

Wavelength (nm)	Ion Source	Relative Radiant Power (514.5 nm = 1)	Relative Photopic Response (to 555 nm, 514.5 nm =1)
676.4	Kr	0.2	0.006
647.1	Kr	1.0	0.175
568.2	Kr	0.3	0.375
530.9	Kr	0.3	0.430
514.5	Ar	1.0	1.000
488.0	Ar	0.8	0.290
476.5	Ar	0.3	0.068
457.9	Ar	0.1	0.001

As discussed in section 3.1.1, the response of the eye is wavelength dependent. Ideally the relative proportion of the total emission of the laser at each wavelength should be in inverse proportion to the response of the eye to give white light. This is usually achieved by attenuating the output at particular wavelengths. However, if this is done at manufacture, the radiant power at some wavelengths (particularly the green) may be less than desirable for some of the effects which do not require multiple colours. As can be seen from the last column in table A.2, the eye's response to the standard output from a Kr/Ar laser at 457.9 nm is a factor of 1000 less than that at 514.5 nm. The useful emissions in terms of a laser light show tend to be restricted to the six lines from 647.1 nm to 476.5 nm.

The means of combining and attenuating radiation at individual wavelengths external to the laser is described in the section on optical components.

A.2.5 Helium-cadmium Laser

The helium-cadmium (He-Cd) laser has been used in the past for entertainment applications but is not widely used today. The main visible emission is at 441.6 nm (blue) at up to about 150 milliwatts. The other major emission is at 325 nm in the ultraviolet, but there are also emissions in the red (636.0 nm) and green (537.8 nm). The use of the three colours potentially could be used to develop a white light laser but it is not believed that this has been used in the entertainment industry.

The He-Cd laser contains metallic cadmium, which has to be heated to about 250°C, and helium gas. The excitation energy is provided by a direct-current discharge, typically of about 1.5 kV. The laser pumping is provided by excited helium atoms which excite and ionise cadmium atoms.

A typical He-Cd laser is between 0.002 and 0.02 percent efficient. Therefore, between 500 and 5000 W of electrical power is required to produce 100 mW laser radiant power. Most models operate on a standard 230 V supply. Convection air cooling is adequate for low radiant powers: the larger units require forced-air cooling.

Beam diameters are between 0.2 and 1.2 mm with a divergence of between 0.5 and 3 mradians (Hecht 1992).

Special hazard considerations include the high voltages which are direct current. If access is gained to the interior of the laser casing then the heater may present a potential burn hazard. If the 325 nm ultraviolet emission is accessible during maintenance or alignment work then special attention to prevent exposures above the maximum permissible exposure at this wavelength is required.

A.2.6 Copper Vapour Laser

The copper vapour laser has recently been used for display purposes in a tour by Pink Floyd (Oxford Lasers 1994). This laser produces emissions at 510 nm (green) and 578 nm (yellow). The main difference between the copper vapour laser and the other lasers discussed so far is that the emission is pulsed rather than continuous. This is inherent in the physics of the laser. Copper metal is heated to about 1500°C to provide adequate metal vapour pressure. Neon is generally added to the cavity to improve the quality of an electrical discharge which directly excites the copper atoms. The atoms can be excited to one of two upper lasing levels. The lifetime is very short (several nanoseconds) so high vapour densities (5 x 10^{19} m^{-3}) are required to ensure sufficient atoms remain in an excited state to produce stimulated emission. The lower laser levels are metastable with a relatively long relaxation time (tens to hundreds of microseconds). This means that these lower levels fill up and laser action stops. The laser process can only start again when these lower levels have emptied. Therefore, the requirement is to produce a lot of excited atoms in a very short period of time and then try to empty the lower levels sufficiently that the upper levels can be populated again. Typical commercial copper vapour lasers operate at between 4 and 12 kHz.

The copper vapour laser is inherently very efficient compared with most other lasers. The pulse of optical radiation may be of the order of 10 ns duration. From a velocity of light of approximately 3 x 10^{8} m s^{-1} (actually slightly less than this in a vapour), a photon travels about 3 m during this time. If the cavity is about 1 m long, the maximum number of passes through the cavity will be 3.

The maximum average power is about 25 W for commercial copper vapour lasers. Individual pulses last from 8 to 80 ns. Assuming 10 ns and a pulse repetition rate of 10 kHz, this gives a peak power of 250 kW for each pulse (25/10000 J/pulse divided by 10 ns to give the peak power per pulse).

The beam diameter for copper vapour lasers range from 20 to 80 mm while the divergence is from 3 to 5 milliradians. The lasers are between 0.2 and 1 percent efficient so a 10 W laser dissipates about 2 kW of heat. This can be removed by forced-air cooling. This laser can operate from a single phase 230 V supply but larger, water cooled devices, require three-phase mains at 415 V (Hecht 1992).

The copper vapour laser uses up the copper metal during operation because it condenses on parts of the assembly where it cannot be heated up again. Therefore, copper wire is added approximately every few hundred hours of operation.

The high voltage, high current, discharges which drive copper vapour lasers present a potential electrocution hazard. A charge may be maintained on the circuit after the laser has been switched off. The high temperatures will present a burn hazard. The switching circuit will normally consist of a thyratron. There may be significant radiofrequency radiation from this device and, potentially, x-rays. The cabinet should provide adequate shielding but caution will be required during maintenance and servicing with the covers removed.

The laser radiation presents a particular concern because of the pulsed nature of the emission.

A.2.7 Gold Vapour Laser

The gold vapour laser operates in a similar manner to the copper vapour laser. The principal visible emission is at 628 nm (red). A gold vapour laser was used alongside a copper vapour laser recently at an outdoor show at Huilongtan Park, Shanghai, China (Messenger 1995).

A.2.8 Neodymium:YAG Laser

The neodymium:YAG (Nd:YAG) laser comes from a family of solid state lasers where the active medium is a solid. The solid is mainly a crystal of yttrium aluminium garnet (YAG) which is doped with impurity ions of neodymium. The principal emission is at 1064 nm, which is in the near infrared. However, the output beam can be frequency doubled to produce 532 nm radiation (green) using a potassium titanyl phosphate (KTP) crystal. These lasers have found widespread use in medical applications and most of the entertainment lasers tend to be modified medical lasers. It is believed that the first use of an Nd:YAG for entertainment took place at Stanford University in November 1993 (Anderson 1994).

The laser rod can be excited by either using a flashlamp, an arc lamp or by using another laser. The last technique is more efficient and increasing use is being made of semiconductor lasers. These can be used in an array and most of the laser radiation can be focused into the Nd:YAG crystal. The optimum pumping wavelength is about 800 nm which is a region of efficient GaAlAs semiconductor lasers. When a flashlamp or an arc lamp is used a small fraction of the emitted radiation is in the pumping wavelength region.

Nd:YAG lasers used in the entertainment industry are operated either continuously or Q-switched. Q-switching produces very short pulses of laser radiation from a few nanoseconds to hundreds of nanoseconds. The average power is no greater, but the energy is delivered in a short pulse.

An example Nd:YAG which is commercially available for use in the entertainment industry has the following specification: output power 40 W (assumed to be the average power); pulse repetition rate 25 kHz and beam divergence 8.0 milliradians (Laser Rays 1994). The laser is pumped using a krypton arc lamp, operates from a single phase 230 V mains supply, generates 4.4 kW of heat and is water cooled. The system comprises a head (0.81 m x 0.41 m x 0.20 m), weighing 36 kg, and a power supply (1 m x 0.66 m x 0.46 m), weighing 118 kg. The laser is controlled via a laptop computer.

The continuing development of semiconductor lasers will ensure that higher powered Nd:YAG lasers will become available in smaller packages with lower electrical power requirements. This will make them increasingly attractive to the entertainment industry because they are generally much more robust than ion lasers producing the same level of brightness.

Nd:YAG lasers containing flashlamps or arc lamps will contain high voltage power supplies and, in the case of the flashlamp, potentially charged circuits when the laser is switched off. These optical sources will also present a risk to the eye and skin of persons working on the laser with the covers removed. The lamps may also be hot and subject to shattering, especially when hot, if mechanically mistreated.

The primary laser radiation from the Nd:YAG laser is invisible (1064 nm). Radiation at this wavelength is still focused by the eye onto the retina and unintentional viewing could therefore result in retinal burns. This radiation should only be accessible during servicing work with the cover removed. However, checks should be made to ensure that the infrared radiation is blocked adequately during normal use of the laser.

The Q-switched laser radiation presents a particular concern because of the pulsed nature of the emission. It would be possible to receive several pulses in the eye from a scanned beam.

A.2.9 Semiconductor Lasers

The semiconductor or diode laser is likely to have a great deal of impact on the laser entertainment industry in the future. Early semiconductor lasers emitted radiation in the infrared region of the electromagnetic spectrum. However, devices are now commercially available which emit at 635 nm (equivalent to the red helium-neon laser) and at lower wavelengths. As technology advances it should be possible to have red, green and blue semiconductor lasers so that multi-colour displays using these lasers will be possible.

Each individual semiconductor laser may emit up to several milliwatts but it is possible to have arrays of these lasers to build up to radiant powers of a few watts. The power source for each laser is usually a few volts. This combined with the small physical dimensions of each laser make the laser system small compared with the alternatives. The use of such lasers for pumping other lasers, for example the Nd:YAG, make the lasing process extremely efficient.

The beam from an individual semiconductor laser is highly divergent. Therefore, collimating optics is required. This may form an integral part of the individual laser package or may be mounted externally. Semiconductor lasers are also available in so-called pigtailed configuration with an optical fibre attached.

Semiconductors generally present a much reduced risk of electric shock but the power supplies required for large banks of diodes may still present a risk. The assumption that a laser is only powerful if it is big does not apply here. For this reason special attention is required to the laser radiation hazard.

A.2.10 Other Lasers

There are a number of other types of laser which could potentially be used for entertainment purposes. One family is the dye laser which makes use of an organic dye in a solvent. These require optical pumping from either a flashlamp/arc lamp or from another laser. The main problem with the dye laser is the potential health effects from the dyes and disposal problems.

A variation of the Nd:YAG laser is the $Nd:YVO_4$ laser which is commercially available with a 0.5 mm thick chip of $Nd:YVO_4$ in close contact with a 2 mm thick KTP crystal. Pumping is provided by a 500 mW semiconductor laser at 809 nm (Randolph 1995). The current maximum radiant power is about 100 mW continuous and the unit is about 38 mm x 38 mm x 100 mm. One suggested application for this laser, albeit at a lower radiant power, is direct projection of images onto the retina.

A.2.11 Summary of Lasers Used in Entertainment

There are a number of lasers used in the laser light show industry. They each have advantages and disadvantages. As technology progresses there is likely to be a trend towards solid state and semiconductor lasers.

A.3 Optical Connection

The laser may be contained within an optical processing system (OPS), it may by coupled directly to the OPS, or the link may be via a fibre optic cable.

Mounting the laser inside the OPS is an ideal option for systems using lasers which are physically small and which require no cooling. Most of the alignment can be carried out before installation. However, for a fixed installation it is still possible to install a large ion laser head within the OPS, especially if the OPS is already of similar dimensions to the laser head.

The most common method of connection for larger lasers is to mount the laser head directly beside the OPS. This requires alignment between the two assemblies.

As fibre optic cables reduce in price and the transmission efficiency improves, remote connection of the laser head and the OPS becomes more attractive. In its simplest form the laser head could be floor or vehicle mounted thus reducing the manual handling problems and the strength of the off-ground support. The fibre optic cable may then be a few metres long at most. However, it is also reasonable to run the fibre over tens of metres, possibly splitting the beam into several fibres. The OPS could then be mounted some way from the laser. The additional factors to be considered from a safety perspective include the quality of the protection of the fibre, probability of damage and accessibility to non-authorised persons. Some of these fibres may be carrying several watts of laser power.

A.4 Primary Optics

The optical systems used for laser light shows are usually separated into primary optics, which covers the optical components connected to the laser head (whether directly or by a fibre optic cable), and secondary optics, which are around the venue and physically remote from the laser radiation source.

The primary optics will vary in complexity depending on the budget available and the type of effects to be produced. Laser effects generally fall into two categories: beam effects, where the beam is made visible, and images, where the beam is projected onto a screen (which may be an actual screen or, for example, a tree or a building). The simplest effect is a straight beam coming directly out of the laser head. Some of the earlier displays, such as that forming part of the Christmas lights down Oxford Street in London, were straight beams. However, to see a laser beam part of it must be scattered into the eye. If there is no scattering medium in the air the beam will not be visible. The laser companies usually use some form of smoke generator (although vapour generator is perhaps a more precise term), but fine rain or light mist is equally effective out-of-doors.

The laser beam can be directed through dispersive optics or it can be scanned. The optical components will be described in the following sections. An image can be generated on a screen by scanning a laser beam. In this situation the ideal is for the beam travelling to the screen to be invisible, which conflicts with the beam effect requirement. If the beam is scanned such that the same point on the image is revisited once approximately every 0.1 s the brain perceives a picture, although there is significant flicker. Once the scan rate reaches about 30 Hz, the image is perceived as solid by most observers and it is not possible to see that it is made up of a scanned spot. The persistence of vision with regard to moving objects was studied by Roget and he presented a paper on this to the Royal Society (Roget 1824). Wertheimer produced a monograph on the perception of motion in 1912. This has been reviewed by Sekuler (Sekuler 1996). This early work formed the basis for the movie film industry. However, it has implications for generating animations using lasers. The work by Roget demonstrated that a solid image could be generated by a scanned object; Wertheimer showed that the brain required a 'blank' between images to produce movement. For movie film this is achieved by presenting a series of still photographs to the viewer. The zoetrope also achieves the illusion of motion by presenting a series of still images to the observer. In this case sequential images are viewed through slits. However, for a proportion of the time, the eye sees no image at all.

The generation of laser animations relies on the image being presented as a series of frames. Therefore it is usual, but not essential, to blank the laser beam between frames. Control data used to achieve this is presented later, with an indication of the relative on to off times. Another significant factor observed by Wertheimer was the ability of the eye to generate motion. An example of one of the experiments performed by Wertheimer was to present a vertical bar to an observer and then present a horizontal bar, ie the vertical bar rotated about its bottom edge by 90°. The observer perceives the bar falling over, or adds information that does not exist.

A.4.1 Scanning Systems

The simplest form of scanning system is to use a hand-held mirror. The beam can be made to dance around and relies on the dexterity of the operator. The control of the beam is limited and there is a high risk of the laser beam going in an unplanned direction. There have been anecdotal reports of this means of scanning being used in, for example, village-hall discotheques with ion lasers up to a few hundred milliwatts.

The laser operator can make use of the movement of a loudspeaker to modulate the laser beam in time with the music. This can be achieved by stretching a rubber membrane over the front of the loudspeaker and mounting the mirror on the membrane. The mirror could also be mounted directly on the central part of the loudspeaker or a cantilever system could be used to amplify the movement (McComb 1988).

Mirrors mounted on mirror shafts can be used to produce Lissajous-type patterns on a screen. An article in a hobby electronics magazine (Goodman 1988) describes a two-motor system which is available in kit or assembled form, complete with a controller. The rotation rate of each motor can be controlled manually, automatically, or by an external source (such as from an audio system).

Most laser display companies use galvanometer scanning. There are currently two models which comprise most of the market: the General Scanning (GS) G120D and the Cambridge Technology (CT) 6800H. The principal difference between the two scanners is that the G120D has a torsion spring which returns the scanner to the central position if the drive signal is lost whereas the 6800H does not. Both scanners operate by rotating to an angle when a voltage is applied to the coil. The technology has been developed for military applications and has been applied through industry to the light show industry. Therefore the precision of the scanners is probably much better than required to produce laser light show effects. A comparison of some of the features of the two types are scanner are presented in table A.3.

Table A.3 Comparison of General Scanning and Cambridge Technology Galvanometer Parameters

Parameter	GS G120D	CT 6800H
Body size	33.0 mm x 33.0 mm x 22.9 mm	34.5 mm x 25.4 mm diameter
Mirror size	10 mm diameter maximum	Typically 24 mm x 12 mm maximum
Mechanical scan angle (peak-to-peak)	20°	40°
Rated maximum scan rate	300 Hz	Not specified but 600 Hz used during setup
Rotor inertia	0.028 g-cm^2	0.015 g-cm^2

Galvanometers used for scanning are usually installed in pairs. The laser radiation is incident on a mirror mounted at the end of the rotating shaft. Rotation of the mirror about its centre line provides a scanning motion in one plane. The beam is reflected from the first mirror onto a second mirror on a second galvanometer mounted at 90° to the first, thus providing a scanning motion in another plane. Complex patterns can be built up by programmed movements of the relevant galvanometers.

The position of the galvanometer is determined by sending a current signal to the coil. Position sensors relay a signal back to the drive card. The movement of the galvanometer is determined by the error in the sensor. The GS units use a capacitive system whereas the CT units use an optical system. The GS units require a drive signal to maintain an angle away from the central position (to drive against the torsion spring). The CT units require no drive signal once the required angle has been reached.

The drive circuit boards provided by the manufacturers are matched to their galvanometers. In the case of the CT units, each board is matched to an individual galvanometer before supply. The GS boards generally drive two galvanometers. Both manufacturers provide position and velocity (differential of position signal) which can be used to ensure that the galvanometer is operating correctly.

Some laser companies opt to manufacture their own drive boards and there are a number of manufacturers in the United States who specialise in drive boards for the entertainment industry. Drive boards are available which are switchable between the two manufacturer's galvanometers and which claim to match the GS units to the performance of the CT units (Makhov 1995). Some of the 'home-made' boards will tend to drive the galvanometers harder than intended by the manufacturer. With the GS scanner this can result in failure of the torsion spring. The galvanometer should still work but the performance will be degraded. Both types of galvanometer may be subject to accelerated bearing wear and potential failure.

The input signal to the drive card is likely to be ±5 or ±10 V to achieve the full swing of the mirror. This voltage level may be supplied from an analogue source such that the galvanometer moves smoothly in sympathy with the source signal (assuming the galvanometer can physically keep up with the drive signal). An analogue square wave can be used to test the performance of a galvanometer system. Alternatively the drive signal may be derived from a digital number, converted into a voltage level from an digital to analogue converter (DAC). The number of bits available will determine the resolution of angular movement of the galvanometer.

There are no uniformly accepted standards for providing signals to the drive boards. However, the International Laser Display Association (ILDA) are working towards a series of standards which have been accepted by several companies, especially in the United States. These standards specify the rate at which signals should be sent to the galvanometers - either 12,000, 24,000 or 30,000 points per second (ILDA 1995). If the show consists of graphics or writing on a screen then the number of points available to generate an image can be determined from the image refresh rate. At 30 Hz, 400, 800 or 1000 points would be available. Not all of these points would necessarily be available for producing an image. Some may be anchor points (used to ensure that a sharp edge appears on an image) or blanked (to ensure that an animated image runs at the same rate independent of how much of the image is actually seen on the screen and to move between images).

The data used to generate an image is usually stored in binary format. One such format used in the UK is as follows (Brown 1996). Each image or animation file consists of twelve bytes of filename, 80 bytes of description, 44 bytes of control values which indicate the animation sequence, 74 unused bytes, followed by the frame data. Each frame consists of a 32 bit word. Y is in bits 0 to 11; x is in bits 16 to 27; bit 12 is blanking and the colour is bits 13 to 15 (bit 13 is on for reflect red; bit 14 for reflect green and bit 15 for reflect blue). The first point in the frame is repeated eleven times (five blanked, followed by six unblanked). The last point is repeated twelve times, eight unblanked followed by four blanked.

An example file for a flat scan is plotted in figure A.1. The y values are constant with time, only the x values change.

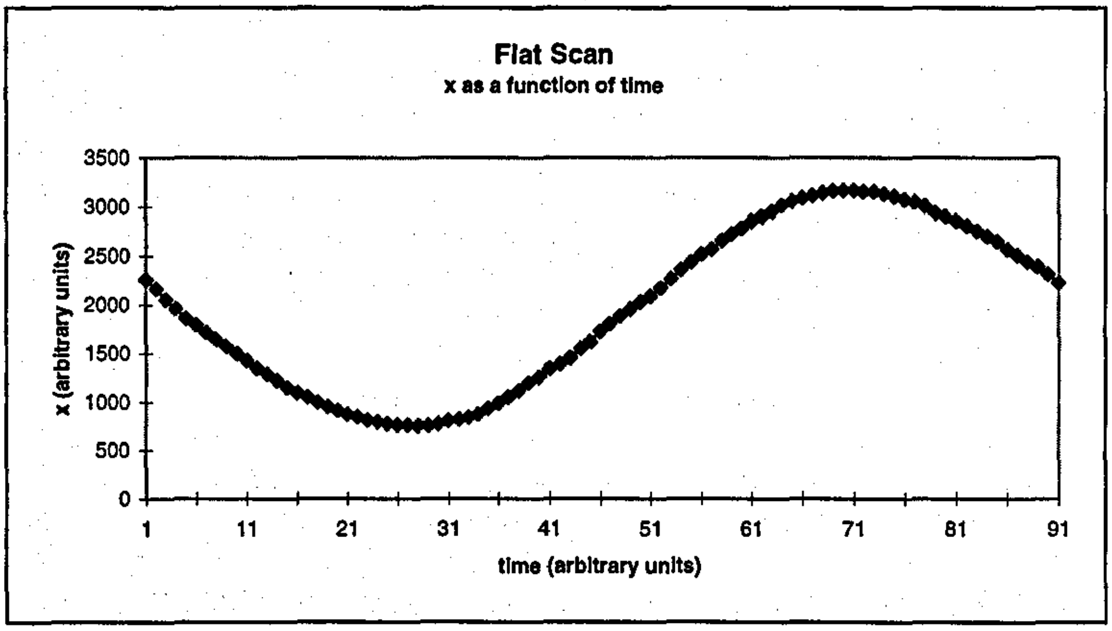


Figure A.1 Values of x as a function of time for a flat scan (y is constant)

The image generated on a screen is shown in figure A.2.

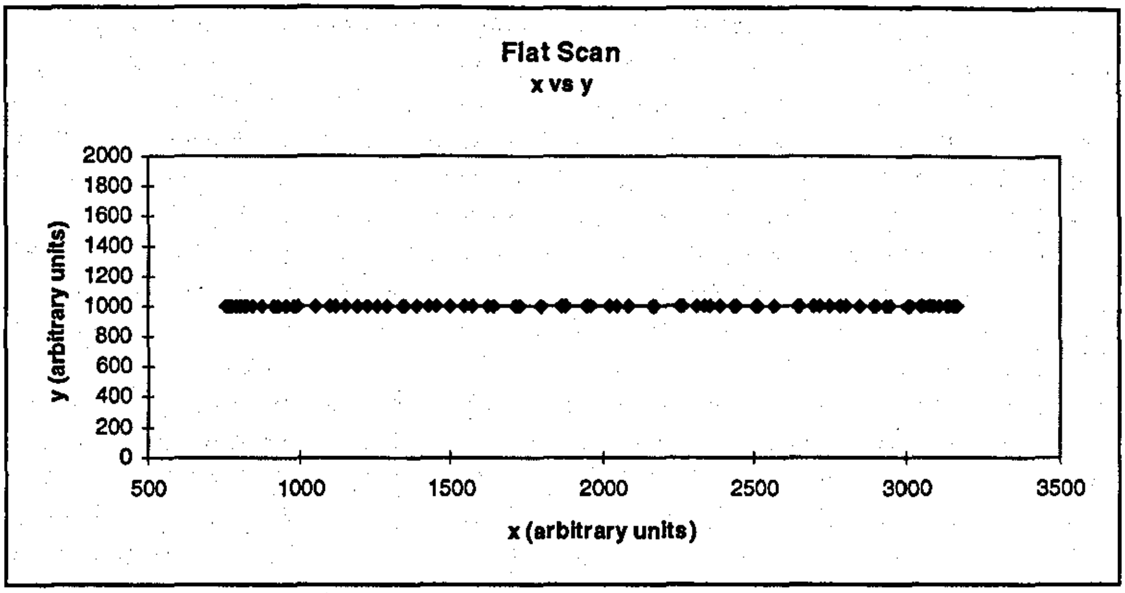


Figure A.2 Flat scan plot of x vs y over a complete cycle (scan to the right and back)

Figure A.3 shows the left hand section of figure A.2 amplified to demonstrate how the spacing of the points used to plot the scan changes with x.

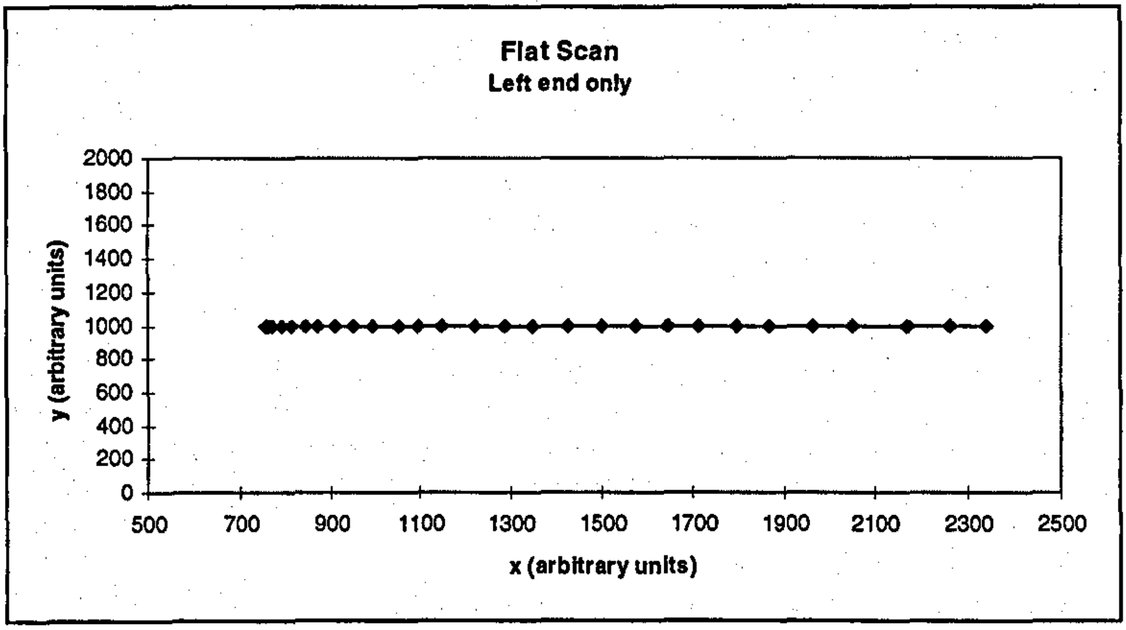


Figure A.3 Left hand end of flat scan (scan from left to right only)

The transfer of laser shows between systems and companies depends on similar performances of the galvanometers. A number of test patterns are available which can be used to demonstrate that the parameters have been optimised. One such test pattern is plotted in figure A.4

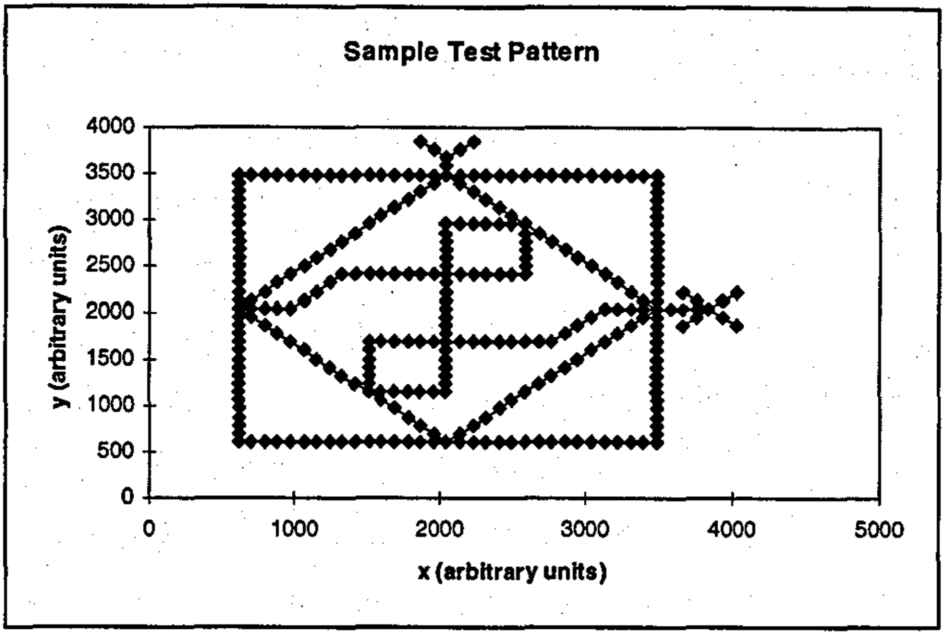


Figure A.4 Galvanometer setup test pattern

It is also possible to use an acousto-optic modulator (AOM) to scan the laser beam. These are normally limited by their scan angle and generally utilise lenses to both reduce the beam diameter before it enters the AOM and to amplify the movement of the beam after the AOM. An advantage of the AOM is that there are no moving parts. The deflection angle (for example about 3° at 70 MHz for 632.8 nm laser radiation) is directly proportional to a radiofrequency (RF) drive signal. Therefore if the RF signal is removed the deflection stops in a time dependent on the acoustic velocity - there is no mechanical inertia in the system. Typical acoustic velocities are a few km s^{-1} (NEOS 1984).

A.4.2 Beam Blanking

If the laser beam is scanned to produce writing, for example, the image produce will be similar to that produced on paper without lifting the pen off the paper. To overcome this problem the laser beam needs to be switched on and off very quickly. This can be achieved by using a galvanometer which is driven using a square wave signal. Typically the beam will be deflected to a beam dump when the galvanometer is at the central position. A voltage is applied to direct the beam through to the scanning galvanometers.

The movement of the galvanometer need not be great. The response time for a CT 6800H driven 2° (relating to a change in drive voltage of about a volt) is about 300 μs (Langram-Goldsmith 1995). It is also possible to use an AOM as a blanking device.

Many laser display systems will be provided with test patterns for setting up the blanking. One such test pattern is presented in figure A.5. The blanking is adjusted until the horizontal tail of the 4 is invisible, with the cut-off between the two vertical bars.

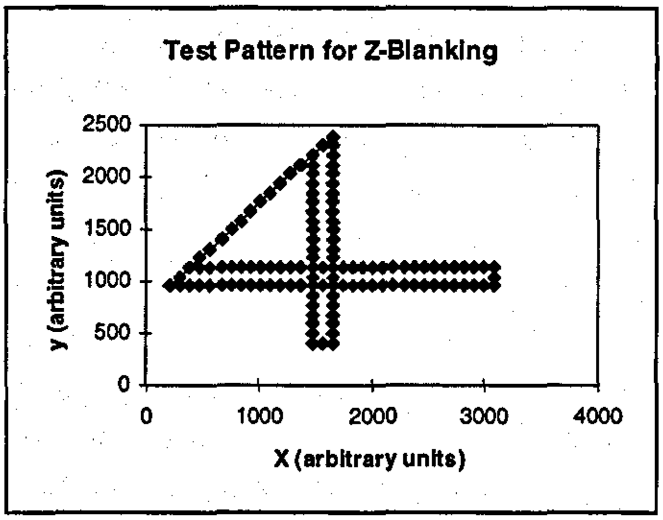


Figure A.5 Test Pattern for Aligning Z-Blanking

A.4.3 Rotary Actuator

It may be necessary to switch the laser beam down different paths to introduce different effects, such as straight beams onto mirrors, or through different optical components. One method of achieving this is to use a mirror which is switched into the beam under operator control. A popular actuator in the UK is the General Scanning GM20 although models are available from a number of other manufacturers. An arm is connected to the shaft of the rotary actuator. With no current applied the actuator is at rest with the arm and mirror lying flat. When the drive current is applied to the actuator the arm rotates lifting the mirror into the path of the beam. A schematic of an actuator is presented in figure A.6 and an example of the application of them is in figure A.7.

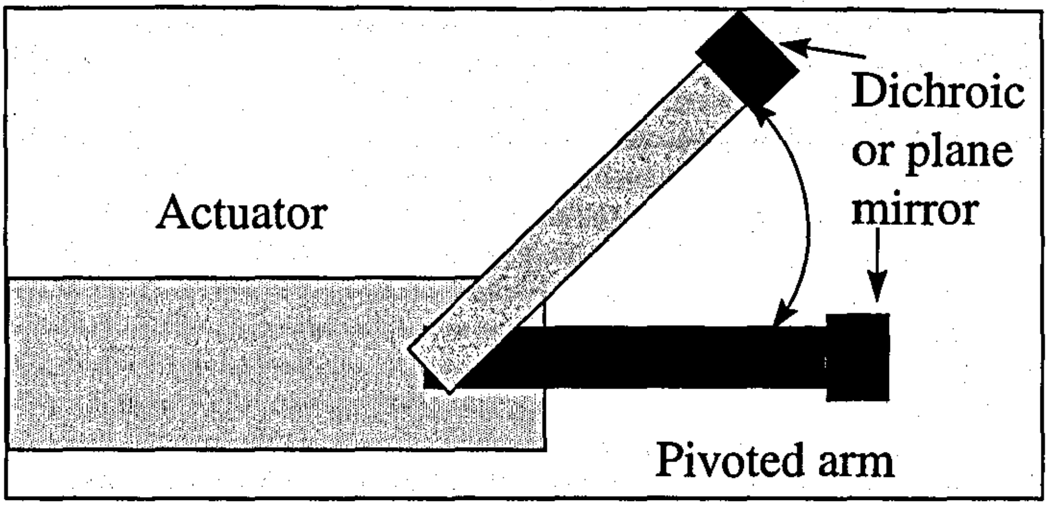


Figure A.6 Schematic of an Actuator

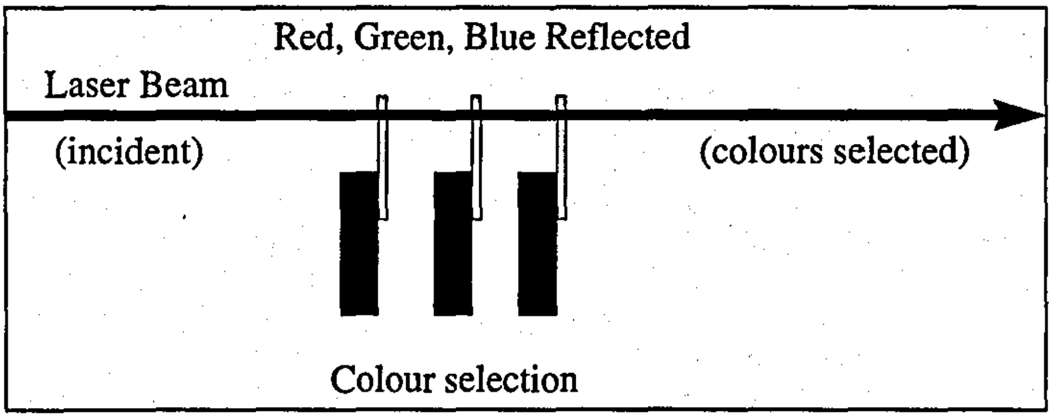


Figure A.7 Example of the Use of Actuators to Select Colours

A.4.4 Beam Splitter

A single laser can be used to produce a number of effects at the same time by splitting the beam into two or more beams. The beam splitter may be a partly transparent metal film, specially designed prisms or may reflect laser radiation at one polarisation and transmit at the orthogonal polarisation. It is also possible to use multilayer interference coatings to selectively reflect particular wavelengths.

Beam splitters are generally rigidly mounted. The laser radiation either always passes through the beam splitter or it is directed to it (for example using a rotary actuator) when required. The beam split may be 50-50 or it may be any other ratio required.

A.4.5 Diffraction Grating

Diffraction gratings are passive dispersive optical devices. The incoming beam is split into a number of output beams. The grating may be either a transmitting device or a reflective device. Transmitting devices are more common in the primary optics. The degree of dispersion is a function of the lines per mm.

If a diffraction grating is used with a laser emitting radiation at a single wavelength, a series of secondary diffracted beams will be produced. There will also generally be the undiffracted central maximum or zero order which, when assessing the irradiance, will represent the worst case exposure situation. If the diffraction grating is used with a laser emitting several wavelengths, such as the mixed gas laser, the diffracted beams will be split into the different wavelengths. The longer wavelength emissions will be diffracted more than the shorter wavelength emissions. The dominant blue and green wavelength emissions from a mixed gas laser can be seen clearly separated from the dominant red emission. The lower intensity remaining wavelength emissions can be perceived by careful observation. Again, the undiffracted central maximum will have the same appearance as the primary beam.

Some installations inhibit the central undiffracted maximum by the use of a beam stop but this is not believed to be common practice.

An optical system may contain a number of different diffraction gratings to give different degrees of dispersion. Diffraction gratings which diffract in two dimensions are also routinely used. The different grating may be mounted on an effects wheel called a 'gobo' in the lighting industry. There is generally a straight-through position with no diffraction grating and then a number of positions with gratings. The gobo is usually driven by a stepper motor under operator control. The gobo may be mounted on the external side of the galvanometers such that any scanned patterns are diffracted. By this means an image can be generated and then replicated a number of times, dependent on the diffraction grating used.

Some installations rotate the diffraction grating. This is especially effective if the output of one diffraction grating is transmitted through a second diffraction grating rotating in the opposite direction. This produces a sea of beams which, if used in conjunction with a mixed gas laser are rainbow coloured.

It is also possible to use diffractive elements to produce images, such as logos from a single input beam. This has the advantage of no moving parts but requires greater input power to produce the same brightness as a similar image scanned image. Currently, each diffractive element is custom made but research is progressing on active diffractive elements where the output image can be changed under programme control.

A.4.6 Luminaire Effects

Laser companies experiment with a number of reflective and transmissive objects to produce interesting effects. A piece of shower glass is effective at randomly refracting an incident laser beam. If this is rotated a wash of colour can be produced on a screen from a mixed gas laser. This is sometimes used in conjunction with a beam splitter such that part of the beam passes through the luminaire to give a background on a screen while the remainder of the beam is directed to scanning system to produce graphical images on the same screen. The beam from a multi-line laser may be passed through a prism before the luminaire.

A.4.7 Three-Dimensional Images

There are several approaches to producing three-dimensional images and all currently have limitations. The first is to use two colours which are scanned onto a screen in slightly different positions. The audience are provided with spectacles which are fitted with different colour filters. Therefore the each eye only sees one of the two images. The limitation with this is that it is restricted to a few colours. There is also the inconvenience and cost of providing all spectators with spectacles.

A second technique is to use polarisation rather than colour to provide two separate images. This technique can provide full colour images but still relies on the audience being provided with spectacles - this time with polarising filters. The technique also relies on the polarisation being maintained and therefore its effectiveness out-of-doors may depend on the weather.

The third technique is the so-called volumetric display. In this case the laser is scanned onto a helical display screen which rotates. Essentially the surface on which the beam is incident is moving in space. Therefore the position of the observer relative to the helix will be important to ensure that parts of the screen are not observed. This system is currently restricted to small-scale displays but is does overcome the problem of the observer wearing spectacles (Belfatto 1995).

A.4.8 Colour Selection

Most of the larger lasers used in the entertainment industry emit laser radiation at more than one wavelength (see section A.1). A diffraction grating can be used to separate out the individual colours but this results in significant losses or complicated optics to regain the energy from all of the diffracted orders. A significant proportion of the incident beam is still contained in the undiffracted order. Dichroic mirrors or filters can be used to separate out the individual wavelengths. For an argon-ion laser this will require one device. For a mixed gas laser this will require up to seven stages to separate the eight wavelengths. The losses in such systems can be considerable.

A recent introduction to the laser light show industry is the polychromatic acousto-optic modulator (PCAOM). Models are available aimed at the laser light show industry (MVM 1995 and Crystal Technology 1993). These devices are polarisation dependent so the input beam needs to be polarised to the manufacturer's specification to gain maximum transmission efficiency (claimed to be typically greater than 90%). Input apertures are generally 3 mm and devices can accept up to 16 W of laser input power.

The PCAOM operates in a similar manner to the AOM described earlier. However, each wavelength can be selected individually, depending on the frequency of the radiofrequency (RF) radiation used to excite the crystal (for example tellurium dioxide). The significant advantage with a PCAOM is that the different wavelengths can be added independent of each other. Typical RF frequencies as a function of wavelength and the RF drive power are presented in table A.4.

Table A.4 Typical Drive RF Radiation Frequencies and Drive Power as a Function of Wavelength for a PCAOM

Channel	Wavelength (nm)	Frequency (MHz)	Drive Power (mW)
1	676	110.25	290
2	647	116.14	260
3	531	149.30	245
4	515	155.87	225
5	488	167.79	170
6	476	173.68	140
7	466	179.35	140
8	458	184.69	140

A.4.9 Lenses

Lenses may be used within the optical system. They may be used to ensure that the beam is focused onto the mirror of a blanking galvanometer. This in turn ensures that the blanking edge is sharp. After the blanking mirror a second lens is required to re-collimate the beam. This simple piece of optics means that the divergence of the laser beam, as quoted by the manufacturer, is no longer valid. The divergence will have to be determined for the system as used.

A second use of lenses is to create a more divergent beam, for example to irradiate an external optical device, such as a mirror ball which is discussed in section A.5.3. The laser beam is likely to be switched to the lens using a rotary actuator. There is also likely to be some form of adjustment or a range of interchangeable lenses to take into account the different distances to the mirror ball in different venues or peripatetic operations.

As has already been discussed, lenses may be used in conjunction with AOMs because of the small degree of scan available with these devices.

A.4.10 Mirrors

The direction of the laser beam within the primary optics will be changed using mirrors. Ideally the mirrors should have the reflecting surface on the front face otherwise ghost reflections will occur from the surface of the glass. Such mirrors are more expensive than standard rear reflection mirrors and may be substituted. The path of any stray reflections should be monitored carefully.

The steering mirrors will normally be adjustable by some means. Mounts are available which can be adjusted from above the beam path. However, these tend to be more expensive and are not commonly used in laser light show systems.

The mirrors mounted on the galvanometers are subject to considerable rotational forces when the galvanometers are driven at high accelerations and decelerations. They need to be able to withstand this.

It should also be recognised that components other than intentional mirrors can produce reflections. These could include the structure of the primary optical cabinet, support structures and tools, rings and watches, etc.

A.4.11 Beam Losses

The various optical components in the primary optical system will cause losses, the degree of which will often depend on the quality of the optics. A fundamental consideration is that what is not reflected or transmitted, is absorbed. At high input laser powers, or more strictly, irradiances the percentage absorption does not need to be very high before the component suffers significant thermal stress. Most laser quality optical components should easily withstand such insults but lower quality components may be used in some installations.

A.4.12 Beam Dump

There may be times when part of the beam is not required. An example is when only the green or the blue emission from an argon-ion laser is required. The other emission needs to be dumped somewhere. Laser radiation above 500 mW is capable of starting a fire, depending on the diameter of the beam and the exposure duration. Therefore the intentional dumping of the beam should be to a part of the system which can cope with the full radiant power of the laser.

A.4.13 Beam Stop

A special form of beam dump is a beam stop. This is likely to be a relatively slow acting (few hundred milliseconds) solenoid with a circular cross section. At rest the tip of the solenoid rod projects (normally down) into the path of the laser beam. When the solenoid is activated, the rod is pulled up out of the beam. Failure of the control system power supply should ensure that the solenoid falls back to the stop position.

The location of the beam stop depends on the design of the optical system. Normally it will be before any splitting of the beam to ensure that only one is required. However, on a simple system it may be in the final optical path before the pair of scanning galvanometers.

It is also possible to use an AOM as a beam stop. However, these are more expensive than electromechanical systems.

A.4.14 Masking Plates

In order to physically restrict the direction of the laser beam from the primary optics it is possible to have a shaped aperture through which the laser beam it emitted. For an installed system this can be a permanent plate attached to the aperture with an appropriate shape. For a peripatetic display, it may be possible to have adjustable plates which can be tailored to each event. As with the beam dump, the masking must be able to absorb the primary laser beam without adverse effect. The edges of the blanking plates should also not be reflective. Otherwise, if a beam clips the edge it will be reflected in an uncontrolled manner.

Masking plates are a simple engineering control which can provide a high degree of protection from the consequences of failure of many of the components in the primary system.

A.5 Secondary Optics

Secondary optics cover the optical components not included within the primary optical processing system. These may be fixed or moving components around a venue and the laser beam normally travels through the air to get to them. Optical systems, such as pairs of galvanometer scanners, which are fed from fibre optic cables are considered primary optical systems although they may be some distance from the laser head.

Nearly all of the secondary optics are mirrors of some form or other. However, the screens used to project images are also included. Examples of each are described in the following sections.

A.5.1 Plane Mirrors

The simplest form of secondary optical component is the plane mirror. There may be a number of these in any venue. Normally they are fixed but some may be under operator control and move using servo motors. The control signals may be transmitted by wire, but some use radio-controlled model servo systems.

The amount of laser radiation reflected from a mirror will be essentially the same as that incident on it. The divergence is also likely to be conserved. Therefore the laser radiation from a mirror should be considered as hazardous as that incident upon it. There is a widely held view among laser display operators that once the beam has been reflected from two mirrors it is "safe". This should not be accepted without a careful consideration of the actual situation.

The mounting and attachment of the mirror are important. For a permanent installation the mirrors may be fixed in position. However, they are more likely to have some degree of adjustment. Mirrors mounted in discotheques and night clubs are likely to be subject to significant vibration. Therefore the mounting brackets should be of such a design that the fixings do not become loose. The attachment of the mirror itself to the support bracket or backing plate also needs to be considered. The most effective system is to have a mechanical attachment system rather than just relying on double-sided adhesive tape.

It is a simple process to mask the mirror position in a fixed installation to ensure that the reflected path is restricted. Should the mirror move, the laser beam would strike a beam dump. Such an arrangement is also possible with some thought for a peripatetic installation but would have to be straightforward to implement.

A.5.2 Diffraction Mirrors

Diffraction mirrors of either one or two dimensional dispersement are used as targets either directly from the primary optical system or from beams reflected from external mirrors. The comments relating to primary mirrors also apply here. Occasionally, diffraction mirrors are mounted in rotating assemblies.

A.5.3 Mirror Balls

Mirror balls have been popular since the early part of the twentieth century for use in ballrooms. Their use has extended to discotheques and night clubs. The mirror ball contains a number of plane mirror facets. They are most effective when rotating at a few revolutions per minute and when illuminated by optical radiation from a number of different directions and the radiation covers the diameter of the mirror ball. Therefore, the most effective optical source is a spot light rather than a laser.

In order to make a laser effective on a mirror ball, the beam needs to have diverged to be at least a significant fraction of the diameter of the mirror ball. This can be achieved by using distance or a diverging lens. A third option is to make the laser beam appear to be a larger diameter than it actually is. This is achieved by using the mirror ball as a target for a spiral graphical image.

The reflections from a mirror ball go in all directions. If the mirror ball is rotated, the reflections will also rotate. In order to assess the exposure condition for the audience who may be subjected to the reflected beams it is important to know the technique used to irradiate the mirror ball, the size of the facets and the rotation speed.

Some laser companies use mirror balls which have either parts of the mirror ball masked off or sections with no reflective facets. This can be used to ensure that the reflections only go up towards the ceiling, for example.

The use of mirror balls out-of-doors may need special consideration. Although a stationary mirror ball can be clamped in position (although they rarely are), a rotation mirror ball will be suspended from the drive motor. The mirror ball will be subject to movement by the wind which, in extreme cases could mean that the laser beam misses the mirror ball completely.

A similar device to the mirror ball is the pyramid spinner. This device projects the reflected beams in one direction - if mounted with the axis vertical, the beam would be reflected down or up, depending on which way up the pyramid was. There are also other variations on this concept of a rotation reflective device which may be encountered.

A.6 Screens

Screens may be purpose designed projection screens, they may be the sides of a building, trees, clouds or any other surface on which the laser radiation is projected to form an image. One of the main benefits of using laser radiation for image projection is that, generally, there is no focusing of the beam. Therefore, the image is in focus irrespective of the distance. This means that non-flat surfaces can be readily used.

A.6.1 Projection Screens

Projection screens may be mounted on walls, permanently suspended from ceilings, on motor drives from ceilings, or temporary installations. Standard photographic projection screens can be used provided they are able to accommodate the irradiance levels without damage. The ideal screen provides diffuse reflections where a fraction of the incident radiation is reflected equally into the eyes of the spectators, such that they can all see the image. However, the amount of radiation incident on the eye will be a function of the distance the observer is from the screen. Many such screens also have a specular reflection component.

Photographic projection screens are designed to be viewed from one side only. However, screens of similar construction are also available for use as back-projection screens. In some laser display applications in discotheques, for example, the projection screen may be in the centre of the dance floor and therefore may be viewed from any angle. These screens are normally a mesh such that a proportion (perhaps 50%) of the laser radiation passes through the screen. However, some screens are solid and act as a Lambertian emitter from both the front and back surfaces. The optical density of such screens is generally about 2, but caution should be exercised in evaluating any directly transmitted component of the incident beam.

The eye hazard from the diffuse reflection from screens should be considered. This will depend on the irradiance at the screen and the closest that persons will reasonably be from the screen. Consideration also should be given to the method used to construct the image: a scanned image will mean that the scattered radiation reaching the eye is also a scanned image on the retina. The path of the laser radiation having passed through the screen also needs to be analysed.

A.6.2 Water Screens

As has already been stated, water forms a good reflector of laser radiation. A fountain of water can be formed into a water screen. This can be used as a target for laser generated images. Again, the degree of transmission of the laser radiation needs to be considered during the display. In addition, the consequences of the water supply failing such that the screen disappears need to be addressed.

A.6.3 Cloud Screens

Depending on the cloud ceiling level, and the density of the water vapour in the clouds, it is possible to use clouds as a screen. In common with other out-of-door laser displays the potential for laser exposure of aircraft need to be considered. Such displays tend to use lasers around 10 W upwards.

Cloud displays are visible over large distances and the potential for distraction of, for example, motorists should be borne in mind.

A.6.4 Trees and Buildings

For large out-of-door laser displays it is common to make use of the surrounding environment. At a stately home or in a park there are likely to be trees surrounding the audience area. The buildings may provide a large convenient screen area. The structure of the stage may also be used as a screen.

Since the screen may not be a flat surface or may be irradiated at an oblique angle, it is possible to use geometric correction hardware on the laser effect control system to correct for this (LSDI 1995).

In all cases the potential for personal exposure needs to be addressed, both under the planned display condition and the reasonably foreseeable incidents.

A.7 Control Systems

There are essentially three types of control systems and any particular performance may make use of one or all of them: manual control; dedicated programmable control; or computer control. The last two may be operated manually or automatically. Examples of the type of control systems are described in this section. Particular safety issues are identified.

A.7.1 Manual Control

The simplest form of laser display control is manual. This can mean manual control of the laser itself, the primary optics and, possibly, the secondary optics. At its most basic level this will be a laser and a hand-held mirror. However, it may be a primary optical system containing a scanning system where the drive signals to the scanning system are controlled, for example, from a signal generator. A line scan can be generated by providing a sine wave drive signal to a single galvanometer. Providing the same drive signal will produce lissajous figure graphics.

Such manual control is unlikely to be seen at anything other than low-budget discotheques, for example. This manual technique is likely to present the greatest risk of inadvertent exposure of people. However, this should be balanced against the likely use of lower radiant power lasers.

A.7.2 Programmable Controllers

Laser display programmable controllers may be truly programmable by the laser operator of may be pre-programmed by the supplier. However, most have some form of operator control. These controllers may be operated by pressing buttons to trigger effects or they may be controlled by, for example, pre-programmed tapes. Pre-programmed laser displays are attractive at night clubs where the disc jockey has control over the music and lights. At specific times they run a show from tape which has been programmed, and the effects aligned, by the laser company.

Graphical images can also include text. An effect from each of the three categories can be assigned to each of the alphabetical keys. The alignment for each effect assigned to each key can be independent and is controlled using the tracker ball. The effects can be made to rotate, flip, etc. They can also be made to change size. Effects can be linked together in a sequence which produces simple animations. The beam shutter is controlled from the `blackout' key. This controller is typical in that it requires password access before the controls become effective. In this case it requires a different password before any of the programmable parameters can be changed.

Automatic systems providing pre-programmed shows generally present less of a risk than those operated by a person. However, a pre-programmed show may be presented by a person with limited training in laser safety.

A.7.3 Computer-Based Controllers

It is possible to complement the programmable controllers with additional control signals provided from a personal computer. However, there are a number of computer-based laser display controllers. In its simplest form, the computer-based system consists of digital to analogue converters (DACs) plugged into a personal computer. The position of one or two scanners (usually galvanometers) are decided by software. The respective angle of each scanner is then determined by the analogue voltage generated at the output of each DAC.

Computer based systems became widely available as computer processing power became available at a reasonable price. Probably one of the first such computerised systems was based on the Commodore Amiga which was designed to control external devices. Lasershow Designer for Windows (Pangolin 1995) has been developed from the Amiga system and uses a Motorola 68030 microprocessor running at 40 MHz on a plug-in board as the main graphics generator. Up to four boards can be used to control up to four scanner pairs at the same time. The computer also controls up to six colour channels.

The advantage of the sophisticated computer based systems such as Lasershow Designer is that the laser show can be developed using the graphical interface in Microsoft Windows. The operator sees the graphical images on the computer screen as they will appear on a projection screen. It is also possible to carry out the development work live, such that the images are developed and projected at the same time.

Lasershow Designer is also able to interface with the musical content of a laser show. The pre-recorded music can be on CD-ROM which can be read by the compact disc reader in the computer. The timing information from the music can be related to particular laser effects using timing codes. The whole show can then be pre-recorded. The growth of standardisation amongst the laser display companies in the United States has meant that Alesis Digital Audio Tape (ADAT) and Aquila SMPTE standards can be exchanged with some assurance that the laser show will perform exactly as planned by the programmer.

A.8 Communication Between Controller and Optics

Most systems use hard wired communication between the laser display controller and the optical systems. This is likely to remain the best technology for permanent installations. However, for events out-of-doors where, for example, several lasers are used, the cable runs may present a hazard to the audience or may be subject to damage. Some laser companies have experimented with the use of radio links between their control consoles and the optical systems. High gain directional antenna systems can be used between two points which should be relatively interference free. However, consideration has to be given to what will happen if the radio link does fail, or if the signals are not understood at either end.

If several lasers are used, each should have an operator who is in a position to take control of the laser if necessary. The communication link between the operators may be by a hard-wire system but it is more likely to be by personal mobile radio (PMR). As is cited in chapter 3, it is possible for such communication systems to interfere with the operation of galvanometers.

A.9 Summary

Laser display systems can be simple devices with a laser and hand-held optical components. They can also be complex computer controlled systems with multiple beams, sometimes from one laser, sometimes from several lasers. However, each system is a product of individual components. Each has its own function and potential hazards. The operation of each of the components of the optical system has been described.

Appendix B

Description of Laser Entertainment Events

B.1 Outdoor Classical Laser and Fireworks Concert A

B.1.1 Introduction

The grounds of a stately home were used to stage an outdoor charity classical concert accompanied by a fireworks and laser display. The laser company, Company A, had submitted the appendix to the HSE Guidance, PM19 (HSE 1980), for approval to the licensing authority, the local District Council Environmental Health Department. The author attended the event at the invitation of the Environmental Health Department because they felt they had insufficient expertise to assess the laser safety.

The audience consisted of about 2000 people who sat either on the grass or brought tables and chairs with them. Many members of the audience were treating the event as purely social and, unlike a performance in a theatre, it could not be assumed that they would necessarily have been looking at the stage. A significant proportion of the audience were consuming alcohol during the performance.

The fireworks display was positioned well behind the stage and appeared to be carried out in a very professional manner. The fire brigade were present and did show a passing interest in the safety aspects of the laser display.

B.1.2 Details of Laser System

Three class 4 lasers were used. The layout of the lasers is shown in figure B.1. Although the original paperwork stated that there would be two Spectra Physics 168 argon ion lasers and one Coherent Purelight argon/krypton laser, there were three argon ion lasers on the day.

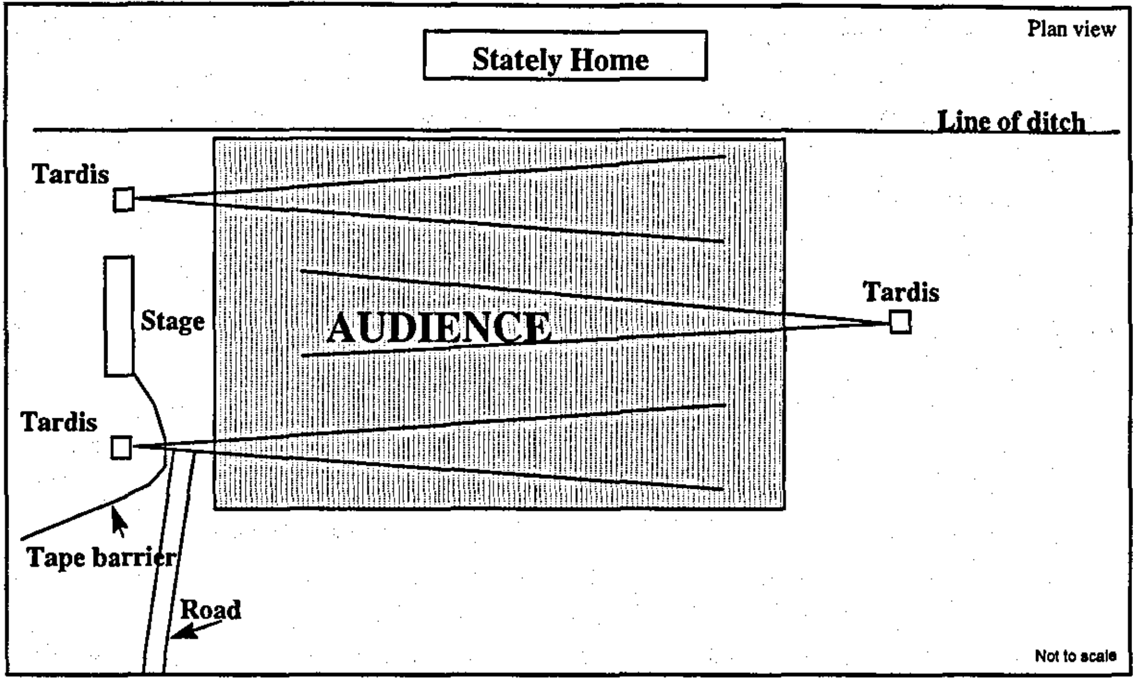


Figure B.1 Layout of Event A

The system used by Company A was claimed by them to be unique. The laser system, optics and control consoles were contained in a prefabricated 'tardis'. This reduced the time required to set up the display. A schematic of the tardis is shown in figure B.2.

The laser show was controlled by the operator at the rear of the audience under directions from a member of the production company. However, there was no direct control of the two lasers beside the stage from this position. This was achieved under radio control to a second operator located in the stage right laser position. This second operator was able to control the two stage lasers from this position. The author was assured that a third person was actually close to the stage left tardis to terminate the laser should the need arise.

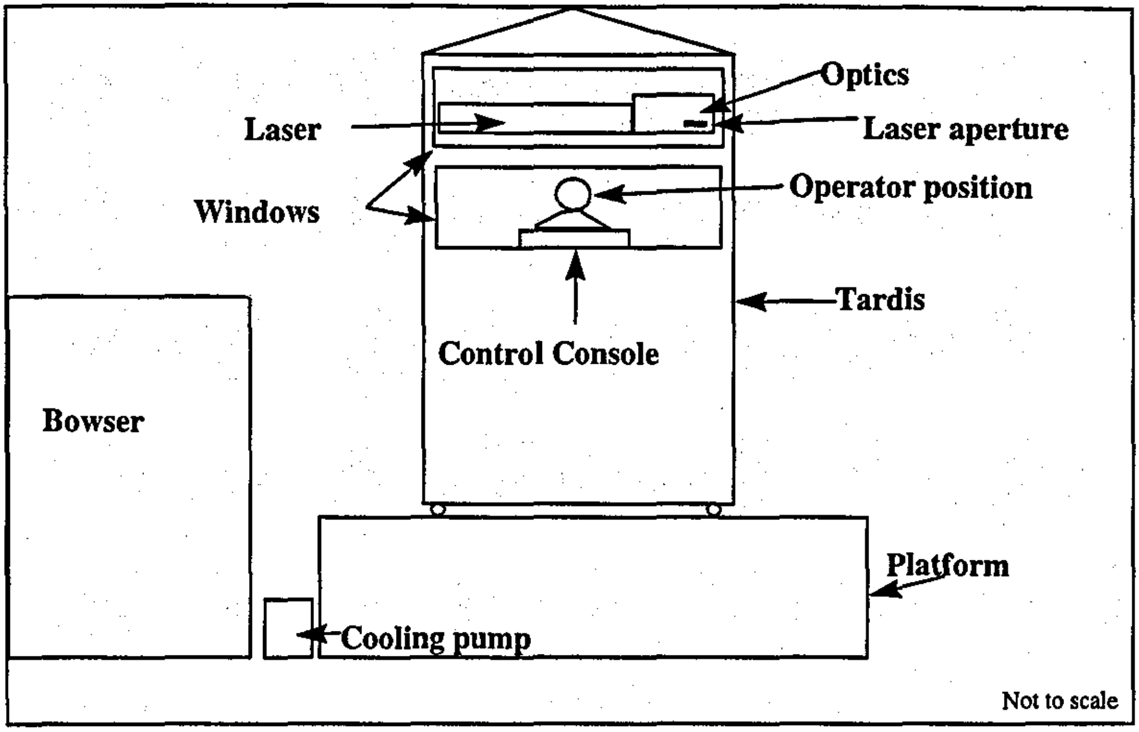


Figure B.2 'Tardis' layout

Three-phase mains power was supplied from a generator located away from the lasers. This was supplied by the production company.

B.1.3 Problems Experienced

A plan of the site with the positions of the lasers marked on it was supplied prior to the event. The layout on the day was rotated approximately 45° counter-clockwise. This reduced the potential for the laser radiation to be directed towards the stately home but was fortuitous rather than planned.

The laser behind the audience was originally specified as being an Argon/Krypton of 2 W nominal output power with a beam divergence of 5.3 mrad. The laser used on the day was a 4 W argon ion with a beam divergence of 3.2 mrad. If the calculations of maximum permissible exposure had been critical from the original laser then, without a site visit, clearance could have been given for a situation that was potentially hazardous.

Company A were aware of the potential for eye injury should the laser radiation be directed into the audience. Measurements taken by the author confirmed that the maximum permissible exposure levels were unlikely to be exceeded on the stage. Masking panels (aluminium plates, painted matt black) were positioned to restrict the beam so that it could only be directed horizontally or at angles above horizontal. There was also an additional section of the blanking plate on the laser to the rear of the audience which blanked out the stage.

The tardis units were mounted on castors typical of the type used on transport cases by sound and stage engineers. The integral locking mechanism was the only means of fixing the tardis in place. The tardis was also mounted on a platform which was constructed on each site. The whole system was not stable and relied on the operator not carrying out any sudden movements.

The blanking plates were fixed in position with adhesive tape. This meant that they were vulnerable and could easily be accidentally moved.

Handheld radios of unknown frequency, but probably in the VHF region, were used to communicate between the operators. It was noted that the transmitters were capable of inducing sufficient current in the laser beam-positioning galvanometers to deflect the laser beam. This should not present a safety issue if the blanking system is effective, but does raise the issue of electromagnetic compatibility (EMC).

The lasers used were cooled by water held in bowsers. The water supply to fill the bowsers came from standpipes around the site. Each bowser took approximately 1.5 hours to fill with water. About 50 minutes prior to the performance commencing the operator noted that the bowser for the laser behind the audience was empty. The cooling water pump had been left running after an earlier test of the laser, the return pipe had fallen out of the bowser and drained the water. The human element then became significant. The operator and support team were now under extreme pressure to refill the bowser in what they knew to be less time than actually required. There was also concern over the state of the cooling water pump which had been running dry for an unknown time.

Sufficient water was put into the bowser by the start of the performance to allow the laser to operate. However, the pump bearings were leaking water adding to the concern of the operator. Just as the performance was due to start the operator realised that a cover, which had been placed over the front of the beam aperture to protect it from the rain, was still in place. This was hurriedly removed, probably disturbing both the position of the blanking plates and the tardis on the platform.

The beams from the rear laser were initially directed into the air, as planned. However, when the operator initiated some 'screen writing' onto the trees behind the stage, the beam was directed into the audience, approximately 20 m in front of the tardis. The operator acted quickly to get the beam up into the air.

The stage left laser did not operate initially and received attention from one of the Company A support crew. When the laser did eventually operate, the beam was low and a video recording taken at the time demonstrates that the beam was directed into the audience on a number of occasions. This may have been due to the blanking plate being moved or due to the tardis moving. It may also be significant that it had been raining all day and the ground was soft: the tardis may have been sinking into the ground.

B.1.4 Conclusion

Human elements played significant parts in the problems that were experienced with this performance. The laser company were aware of the hazards, although they were not able to quantify them, and appeared to be sincere about their desire to keep the beams out of the audience. Better engineering could have prevented most of the problems they experienced. An interesting problem here was the electromagnetic compatibility (EMC) issue where the radio interfered with the galvanometer. Proper screening of the optical system would have prevented such interference. However, it does raise the issue of other parts of the laser display system which could be subject to EMC problems.

The EHO was fully capable of assessing the electrical, mechanical and water safety of the laser display. However, he had no expertise of assessing laser radiation safety. The provision of plausible calculations of laser beam exposure conditions by the laser company caused some concern. When these were analysed in some details it was apparent that they did not relate to this specific event.

B.2 Outdoor Classical Laser and Fireworks Concert B

B.2.1 Introduction

The performance at this stately home was similar to that at Concert A except that the event was a commercial venture and a different laser company, Company B, were used. The invitation to attend came from the production company. The local Environmental Health Officer did not ask for any details of the laser display and no information was volunteered by either the production company or Company B.

Discussions prior to the event revealed that the laser company were not convinced that the laser radiation should be kept away from the audience. The show was a limited version of what they would normally do because of the author's presence. However, the laser operator considered that the audience attended such events in order to be 'irradiated by the laser'. No calculations were available to allow a judgement to be made on whether scanning the audience with the laser radiation would present an acceptable risk, both as intended and in the event of a failure condition.

The audience consisted of about 8000 people. The layout was similar to Concert A but was very cramped.

B.2.2 Details of the Laser System

Three lasers were used in a similar layout to the Concert A event. Each was stated as being 4 W nominal radiant power. The laser to stage right was an argon/krypton which was capable of being directed 360° around its position. The lasers were mounted on scaffolding which was constructed for each of the three laser positions.

Laser cooling was provided by a different means for each of the three lasers. The laser at the rear of the audience was cooled by water from a bowser. There was only one standpipe which was located close to the stately home. The site of the performance was on a slope rising away from the stage. This presented some problems with water pressure. The laser to stage right was cooled by water from the same standpipe but with continuous feed via a small reservoir. The third laser was cooled by re-circulating water from a refrigeration plant.

All three lasers were controlled from the position of the laser at the rear of the stage. This required a control cable to pass through the audience towards the stage.

B.2.3 Problems Experienced

The organisation of the laser company was less than ideal. They explained that they preferred to set up on the day before. However, since this event was being staged throughout the country and had been held the evening before across the other side of the country, the stage would not be in place until the morning of the performance. The stage is the key component of the show. All ancillary equipment, such as the lasers and sound systems are positioned relative to the stage. The generators for powering the lasers would also not be in position until the stage arrived.

The construction of the scaffolding towers and the installation of the laser and associated equipment took until early evening. The public had access to the site from about 6 pm with the music commencing at 7 pm: the lasers were due to start at 9.30 pm. Company B were not in a position to test the lasers until about 8.45 pm. This meant that the audience was essentially complete with about 8000 people present.

The operator claimed that the control optics always defaulted to a high elevation when switched on. This was proved to be erroneous because the beam was directed at the rear of the head of a member of the audience approximately 10 m from the laser. Although the operator reacted quickly to switch the beam off, the irradiance would have been sufficient for the risk of eye injury to have been high.

The operator carried out the alignment procedures on all three lasers and was under a high degree of stress because of the time limitation and the difficulty of moving through the audience to the other lasers. The laser control position to the rear of the audience was eventually surrounded by the audience. This encouraged a number of interested people to come along and ask questions of the operator.

When the show commenced a significant proportion of the effects involved irradiation of the audience. The author found the radiation from the stage lasers uncomfortable at about 100 m. Many members of the audience were being exposed at much shorter distances. The performance was recorded on video tape and the laser radiation often struck the camera lens.

Helium-filled reflective balloons were on sale during the event. Had the laser company been concerned with keeping the laser radiation out of the audience then these balloons, under some conditions, could have resulted in a potential exposure pathway for the audience. However, in general, such balloons would have resulted in an increased beam divergence for the reflected beam.

B.2.4 Conclusions

The attitude of the laser company towards laser safety gave some cause for concern. However, the Environmental Health Officer did not get involved and the production company did not seek any safety assurances from the laser company. Therefore, there was no external control over what the laser company were doing.

There was no blanking of the beam because the laser company did not consider this necessary. The admission by the laser company that the show had been sanitised slightly because of the author's presence raises questions regarding the potential for eye injuries at events where this company is involved.

The laser company were able to produce sample calculations which purported to support the argument that the exposure of the audience to the laser radiation was at levels below the maximum permissible exposure. However, the calculations did not relate to the specific show given and certainly did not take into account many of the beam effects used.

B.3 Outdoor Display at a Marina C

B.3.1 Introduction

The laser display at a Marina was part of a Twinning Association event organised by the proprietor of the Marina. The author attended at the request of the local Environmental Health Officer since the District felt it had insufficient expertise to assess the laser radiation safety issues arising from the event. However, he was fully competent to assess the electrical and mechanical aspects of the event.

The laser was provided by Company C as a favour to the proprietor. The laser display was set up and operated by a freelance show designer.

The event was staged to raise money for the Twinning Association. Two German Minesweepers from the twin town were based at the Marina for the duration of the event. The proprietor had been on the local radio several times during the week to complain about the involvement of the Environmental Health Officer.

A public footpath passed through the site of the laser show and was the main cause for concern by the licensing authority.

B.3.2 Details of the Laser System

Two Coherent Innova 70 2 W argon ion lasers were mounted on piles at the marina. A control point was set up on the deck of one of the German Minesweepers.

The lasers were water cooled using water from standpipes located on the Marina. The mains transformers were mounted at the top of the piles close to the laser.

The layout of the site is shown in figure B.3 in plan. The proposed arrangement for the mirrors and laser beams is shown in figure B.4: the final arrangement is shown in figure B.5.

The laser operator was in radio contact with a sound engineer who was responsible for the recorded music to accompany the laser display. Four separate performances were planned: only three took place - see section B.3.3.

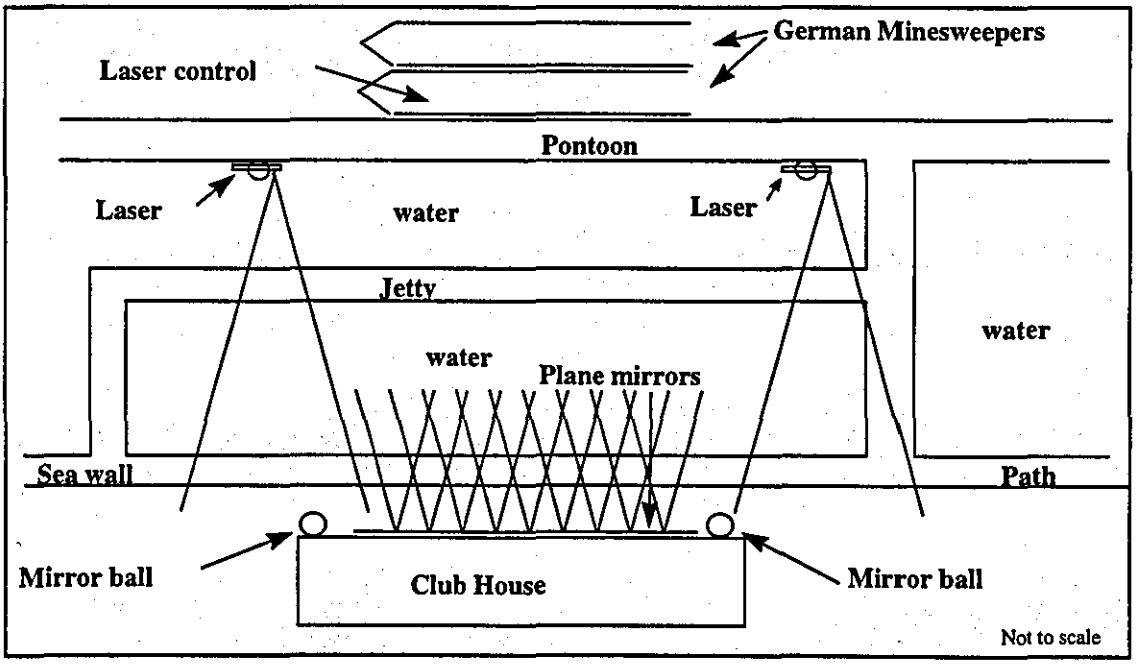


Figure B.3 General layout of Event C

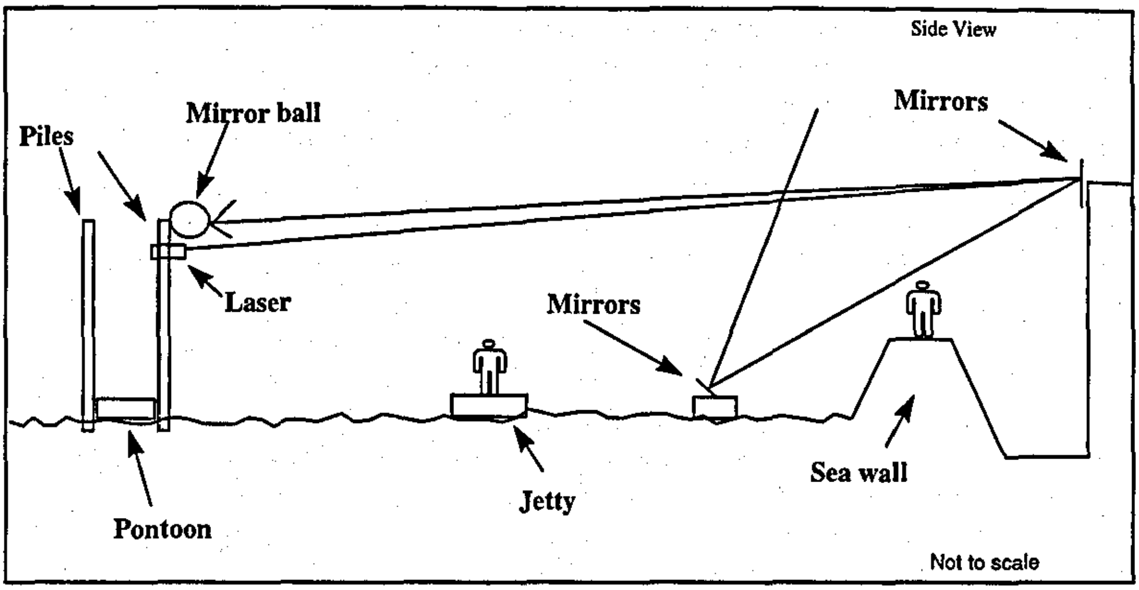


Figure B.4 Original Planned Layout for Event C

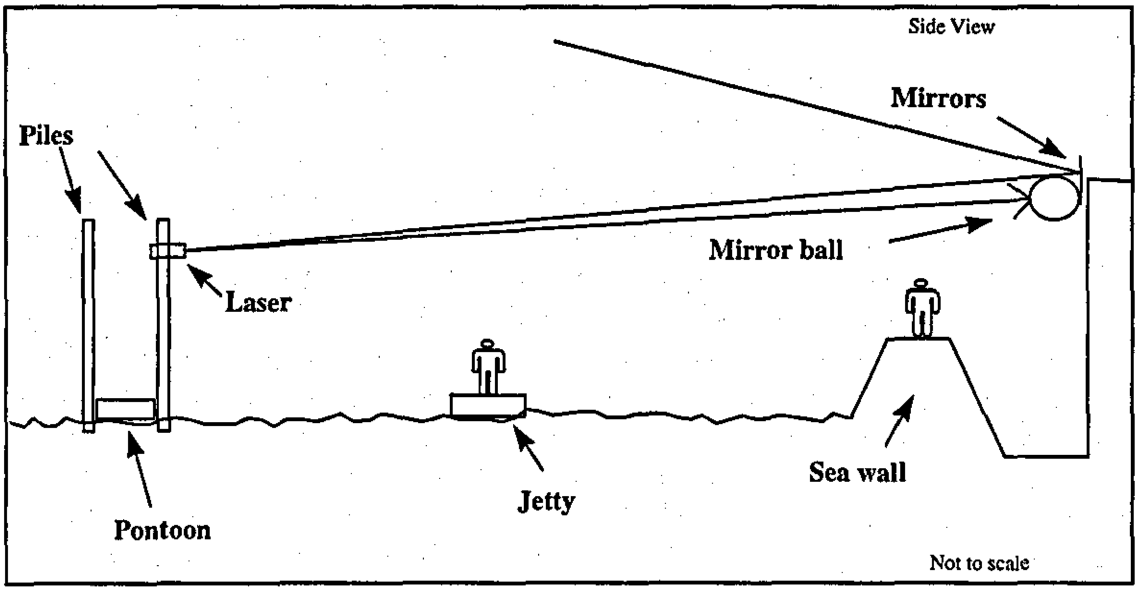


Figure B.5 Final Layout of Event C

A fun-fair was constructed during the days before the event. Some of the final components were constructed on the day of the event. The lasers and mirrors were installed during the evening prior to the event. All of the alignment was carried out during the night prior to the event.

B.3.3 Problems Experienced

The laser operator was aware that irradiating the audience with laser radiation was undesirable. Pressure from the Environmental Health Officer restricted the number of mirrors and the position of the mirrors to areas away from accessible areas.

During the day of the performance a helter-skelter had been constructed behind the Club House. The top of the helter-skelter was in a direct line with the laser radiation should the beam either miss the mirrors on the Club House or if the beam was larger than the mirror. The proprietor agreed that this attraction and an octopus which raised riders into the path of the beam would be closed down during each of the performances.

The lasers were mounted on piles. No account had been taken of the possibility of the piles moving as the tide went in and out. Therefore, the lasers had been aligned with the mirrors, and blanking plates fitted, with a particular tide state. This problem was identified approximately 1 hour prior to the timetabled start of the show.

The operator was not familiar with the control console. He had used similar versions but, because the console operation was heavily dependent on the version of software it was running, he had to familiarise himself with it. The major problem was that all of the effects had been programmed in during the night and supposedly saved to a floppy disk. The data had not actually been saved. This was discovered about one hour before the start of the show.

It was decided to proceed with the operator driving the show live. The lasers were re-blanked to limit the beam to at least 3 m above the height of the footpath. The Environmental Health Officer maintained radio contact with the operator throughout the show. Due to the time delay, the show started about an hour late, only three performances took place.

It was difficult to judge how many people turned up to the event. Two thousand had been expected. However, it was considered that the proprietor put a number of people off by commenting adversely about the Environmental Health Officer's interest in the laser safety on the local radio.

B.3.4 Conclusion

The only potential for exposure was during the setting up process. However, it is suggested that measures to restrict exposure were only taken because of the presence of the Environmental Health Officer. The failure to store the programme data put the operator under a lot of pressure.

Laser radiation exposure was an issue at the early stage of the design of this event. However, the mechanical issues, such as movement of the lasers and optical systems in relation to the rest of the venue, including mirror systems, and the failure of the computer system to store the show, generated the laser radiation safety issues closer to the performance time. The EHO was fully qualified to assess the mechanical issues but was not confident with the implications of the changed exposure situation.

B.4 Drive-In Movie and Laser Show D

B.4.1 Introduction

This display at an airfield was a bonfire-night fireworks display promoted by a local radio station. The laser display company will be referred to as Company D. The author attended to support the District Environmental Health Officer who felt he had insufficient expertise to assess laser radiation safety, although he was fully competent to assess the other hazards, such as electrical and mechanical hazards.

The operator was not able to provide measurements or calculations to support the planned exposure of the audience to the laser radiation. These calculations had to be carried out by the author using information supplied by the laser operator.

B.4.2 Details of the Laser System

The display was carried out with a single 20 W Spectra Physics argon ion laser. This was loaned to Company D by the manufacturer. The laser was mounted on a scaffolding tower adjacent to a mobile 'drive-in movie' projection caravan. The caravan provided a convenient mask to restrict laser radiation from being directed below horizontal (at about 3 m) in the direction of the audience.

The laser was used to project cartoon images on to a screen which, at other times, was being used as the projection screen for the drive-in movie. A mirror ball was positioned on the screen. Initially, the paperwork from the laser company indicated that the mirror ball would be 1 m in diameter with 0.015 m facets and located at the top of the screen. On the day the mirror ball was 0.76 m (30") diameter with 0.01 m facets and it was mounted at the bottom of the screen. Mirrors were attached to the support tower for the screen at a height of about 3 m and were directed into the sky.

The main concern with this display was the radiant power of the laser. The nominal ocular hazard distance was calculated as 2 km. The potential for any hazard could be minimised by directing the beams into the air. However, the beam path between the laser and the mirrors was horizontal. The mirror ball also potentially redirected the laser radiation into areas occupied by the public.

B.4.3 Problems Experienced

The changes from the original specification with the mirror ball meant that calculations had to be repeated on location. The Environmental Health Officer was prepared to insist that the mirror ball should not be used but required evidence to support this. The calculations demonstrated that the maximum permissible exposure levels would only be exceeded if the beam was not expanded and the mirror ball stopped rotating. Undertaking calculations under the time pressures inherent in live performances is not easy. The change of mirror ball was not considered significant by the operator, which demonstrated that the safety implications were not appreciated. However, it was reasonably foreseeable that equipment may fail and be replaced, so operators should be in a position to assess any way that the safety judgements are invalidated.

The laser was powered from a mobile generator which had been hired by the event organisers. The power cable was too short. The generator had to be dragged with a lorry to the correct position. This in itself was a hazardous operation but, since the operation took several hours to complete, meant that the laser company were pressed for time. The Environmental Health Officer had asked that the author should be happy with the laser safety aspects before the public were admitted to the site. This was not possible. The surrounding roads were becoming blocked with traffic and the police decided that the public had to be admitted. This demonstrates the importance of being able to judge the whole safety issue. A specialist laser safety adviser may not be in a position to make the necessary judgement. However, enforcing officers also need to be able to put the laser safety issue in perspective.

The laser operator assured the author that the laser optics were aligned and blanked off at his premises such that exposure below horizontal was not possible. However, this relied on the laser and optics being horizontal. The operator had no means of checking this. When he carried out the final alignment he removed the blanking plates anyway.

At the start of the first of two performances the laser tripped out due to a temperature problem. This was rectified within five minutes and the performance continued.

B.4.4 Conclusion

This event demonstrated that the laser company does not always do what it says it will do. The change of mirror ball was considered a minor change by them, as was the change of position. It showed a lack of understanding of the safety issues.

The influence of parameters outside the immediate control of the laser operator such as power cables not being long enough and the laser overheating add to the pressure operators are under.

Laser radiation became the main safety issue at this event, despite the other hazards. This was mainly because of the difficulty of carrying out the assessments under time pressures.

B.5 Trade Exhibition E

B.5.1 Introduction

Company E had been employed to put on a laser display as part of an advertisement on a stand at a trade exhibition at a Conference Centre. The author acted as Laser Safety Adviser to the venue and particularly gave advice to the venue manager responsible for radiation safety. The use of lasers at the venue was infrequent and the manager considered his investment in time to gain the necessary expertise was not justified. He was fully competent to assess all non-laser-radiation hazards.

B.5.2 Details of the Laser System

A 4 W Spectra Physics 168 argon ion laser was to be employed on a trade stand approximately 5 m by 5 m. The laser was to be mounted below a table with the laser radiation directed vertically up past a personal computer in a perspex tube. Access to the keyboard of the computer was possible through a cut-out in the side of the tube (figure B.6). The beam was then directed from two mirrors to beam stops at the edges of the stand. The structure of the stand was made from highly polished stainless steel.

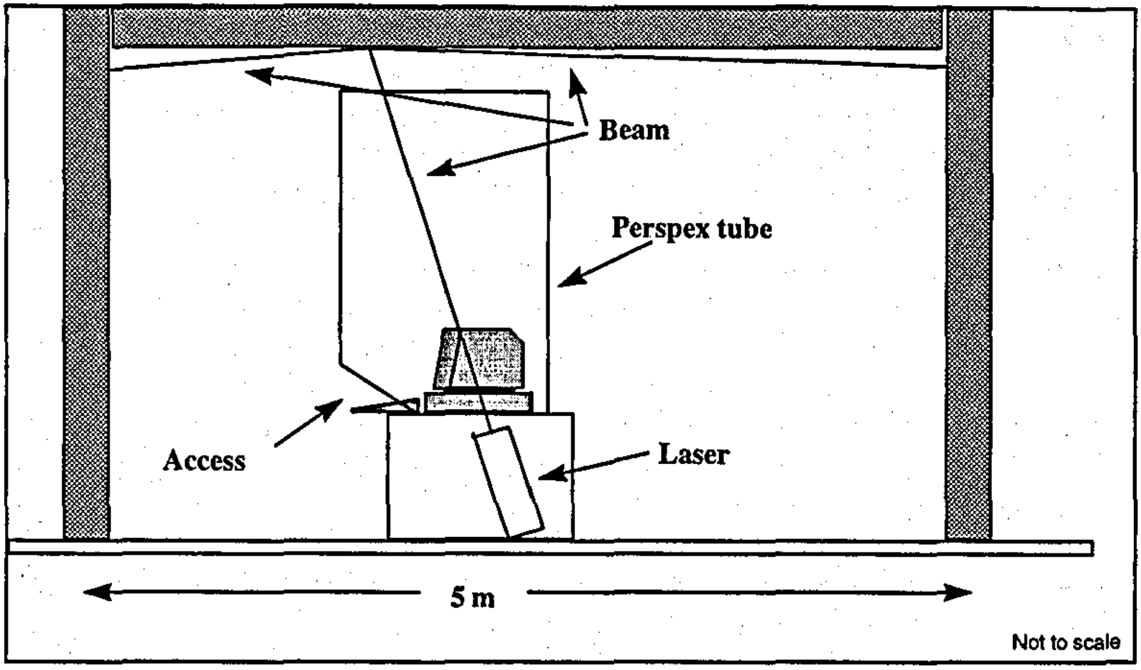


Figure B.6 Trade Exhibition

B.5.3 Problems Experienced

The diagrams of the display suggested that access to the laser radiation was relatively easy. The company were asked to justify the need to use such a high powered laser in such a small environment. They claimed it was the smallest laser they had.

A site visit during the construction of the display stand also gave cause for concern. The structure was not substantial and subject to displacement when people moved across the floor. It was therefore likely that the beam could become misaligned either with the mirrors or with the beam stops.

The author suggested to the venue manager that the laser should not be used because the safety of the visitors could not be assured. This was supported by the venue manager and the laser was not used.

B.5.4 Conclusions

The task that this laser was required to perform could be adequately achieved using a much lower powered laser, such as 20 mW. Blanking panels could have been installed to ensure that the laser radiation would not be accessible to the visitors. Consideration should have been given to the stability of the display stand.

This was an example where collaboration at an early stage could have overcome the problems. It is likely that the companies involved had put on similar displays at other venues without any questions being asked. Calculations of the times to exceed the maximum permissible exposure levels under reasonably foreseeable fault conditions should have alerted the laser company to the risk of the display they intended to put on.

The main safety issues here related to mechanical aspects of the design and construction of the display stand. The failures here made the laser radiation the main issue. The venue also took account of the potential litigation resulting from an incident or accident involving a visitor to the exhibition.

B.6 Trade Conference F

B.6.1 Introduction

Company F had been employed to provide laser effects as part of a conference for insurance sales representatives at a Conference Centre. The author acted as Laser Safety Adviser to the venue and particularly gave advice to the venue manager responsible for radiation safety.

B.6.2 Details of the Laser System

Two Spectra Physics 168 4 W argon ion lasers were used. One was installed in the projection room above the entrance doors to the theatre hall. The other laser was mounted at the rear of the stage. Both lasers were controlled by the operator located in the projection room.

The laser in the projection room was used to sign-write on a screen on the stage. The laser on the stage was initially used to produce a fan of laser radiation above the audience and to sign-write on the walls to the side and rear of the auditorium. At a predetermined point in the performance the stage laser was to produce a fan of laser radiation below the screen on the stage. A smoke generator was used to produce a fog to hide a car which would then appear through the fan of laser radiation.

B.6.3 Problems Experienced

The projection room in which the laser was installed was very cramped. Cooling water hoses came through the door which meant that the door could not be shut. The optical bench was operated with the covers removed and was positioned at about chest height. The radiation was directed through the glass screen with a gap of about 0.5 m. There were significant specular reflections around the projection room. However, measurements were not carried out to quantify the hazard from these.

The car, which was positioned behind the stage, was hidden from view during the first part of the performance by a venetian blind. This was to be operated remotely by the laser operator. The author was assured that this was interlocked such that the laser optics could not direct the radiation down until the blind had been raised. It was also pointed out that the operator could see the blind and would not activate that part of the sequence until he was sure that the blind was out of the way.

During a run-through of the display the venetian blind failed to raise but the laser operator, who later admitted that he could not see the blind with the laser on for the first part of the show, still activate the relevant part of the sequence. A fan of radiation was directed across the auditorium at about head height. The author was the only person in the direct line of the beam and fortunately he was, at that moment, watching the operator through the projection room window, ie facing the other way. The operator terminated the exposure promptly.

The car which was to pass through the laser beam had to have a driver in it to ensure that it did not go off the end of the stage into the audience. Concern was expressed to the organisers about the number of specular reflectors which could potentially direct laser radiation at either the eyes of the driver or into the audience. This was accepted and measures were taken to mask items such as the door mirrors.

B.6.4 Conclusions

This display showed that the operator had little concern for his own safety or for those who may have been in the vicinity of the projection room. It also showed that the operator had not tested the interlocks connected to the venetian blind, if they existed. The operator was visibly shocked by the potentially hazardous irradiation of the auditorium and probably learnt a good lesson.

The potential for stray reflections from items introduced into the beam had not been considered, even though some of these were actual mirrors. It was understood that no instruction concerning laser safety had been given to the driver.

The design of the event was such that laser radiation issues should not have predominated. The failure of the car to stop before it reached the edge of the stage presented a risk of death to those in the auditorium. The hazard was considered to be adequately controlled and the venue management considered that they could make the necessary judgements on the adequacy of the control measures. The main concern of the venue was that the laser radiation was something outside their area of expertise. Most importantly they considered they did not have a ‘feel’ for the magnitude of the risk associated with a given exposure situation.

B.7 Medical Laser G

B.7.1 Introduction

Entertainment is not the only time when laser radiation can potentially put the public at risk. Equipment which utilises laser radiation is often exhibited at trade exhibitions. The exhibitors like to demonstrate the equipment in operation.

Company G had been given permission to exhibit a class 4 surgical laser on a display stand at a Conference Centre subject to approval from the NRPB. The exhibitors wanted to demonstrate the cutting capabilities of the laser by giving visitors to the exhibition stand the opportunity to cut apples.

B.7.2 Details of the Laser System

The laser was a 30 W carbon dioxide surgical laser. This type of laser is generally used for gynaecological surgery. In an operating theatre it would be under the control of a surgeon or consultant trained in its use with the minimum number of support staff necessary.

B.7.3 Problems Experienced

It was difficult to see how the exhibitor could control the potential exposure of its own staff, visitors operating the laser and other visitors. Since the laser was designed to cut people, given the opportunity it would do so. The exhibitor was advised that such use was not acceptable as presented.

The Board was contacted the week before the exhibition was due to take place. The exhibitor had finished planning for the event six months previously. Early consultation may have provided a solution whereby the laser could have been demonstrated.

B.7.4 Conclusion

Laser equipment which can potentially put visitors at risk is routinely displayed at trade exhibitions. The Board's contact with the Conference Centre means that it usually can contribute to the venue's decisions on whether such equipment can be allowed to be demonstrated. However, this venue is only one of a number in London alone where such demonstrations are taking place.

Marketing staff may not have the necessary laser safety expertise. Manufacturers and distributors should ensure that consideration is given to this when products are launched or exhibited.

One of the main factors here was training. The product, in normal use, would be operated by persons who have been trained in both the medical aspects of the procedure and the safety aspects of the laser, including the laser radiation. The procedure relies heavily on administrative controls and personal protective equipment. Such control measures are not adequate when laser products are used by untrained personnel, except under extremely well controlled conditions.

B.8 Laser Games H

B.8.1 Introduction

There are a number of different laser 'tag' game systems which operate on a similar principle. Participants have a 'gun' which incorporates a visible laser and an infrared light emitting diode. The former acts as an aiming device while the latter transmits information to various targets. Each player also has a body pack which includes various target receivers.

B.8.2 Details of the Laser System

Information was provided by one of the laser game manufacturers (Megazone, 1994) and is understood to be typical of other systems in use.

The laser gun contains a laser diode emitting at 635 nm (+10 nm, -5 nm) and is part of a system using the name Phasar. The diode manufacturer's specification gives the radiated power as 3 mW (Philips, 1993). However, the specification for the manufactured gun states the following:

Table B.1 Specification for laser gun

Classification (to BS EN 60825: 1992)	Class 1
Maximum radiated power	0.95 mW
Maximum emission duration	200 ms
Maximum pulse rate	4 Hz
Divergence	3.0 mrad
Spot size at lens	6 mm x 4 mm ± 1 mm
Spot size at 5 m	contained within 15 mm diameter circle

The laser games are normally operated as a franchise. Information is supplied to the franchisee on how to operate the game safely. The instructions include a section on supervision and state that the players should "avoid pointing the Phasar into their eyes or the eyes of other players".

Other systems visited by the author, have Class 2 warning signs on the guns.

B.8.3 Problems Experienced

It is assumed that the laser radiation is coincident with the infrared radiation. Therefore, there is an incentive for the players to aim the laser at the target area of the opponents. It has been observed that some of the guns do not have the two radiations coincident. Where this has been observed, the laser radiation has always been directed higher than the light emitting diode. This error is adjusted for by skilled players. One particular system was sufficiently out of alignment that aiming at the opponent's head provided the best correction for hitting the chest pack at a distance of about 3 m.

The justification for the assignment of the product to class 1 is interesting. The relevant standard at the time was BS EN 60825: 1992 (BSI 1992). Light emitting diodes were not included within this Standard and therefore only the diode laser had to be taken into account. The accessible emission limit for class 1, as given in table 1 of the Standard, is 1.05 mW for a single 200 ms pulse. As soon as more than two pulses are emitted the product becomes class 2. The classification of these products under BS EN 60825-1: 1994 (BSI 1994), which includes light emitting diodes, is likely to result in the products being assigned to class 3B.

B.8.4 Conclusion

Most of the laser games use lasers which are class 2 under BS EN 60825: 1992 and deliberate exposure of people's eyes should be avoided. Repeated exposure may increase an individual's aversion or blink response time. A simple test jig could be supplied by the manufacturers to ensure that the laser radiation remains coincident with the infrared radiation. There are likely to be a number of other hazards associated with playing these laser games. These will include the chemicals used to produce the fog effect, the loud music and the potential for impact with the facility structure under reduced, or strobed, lighting conditions. Local authority EHOs are likely to have adequate expertise to assess these other hazards.

Appendix C

THE CHARTERED INSTITUTE OF ENVIRONMENTAL HEALTH

NATIONAL RADIOLOGICAL PROTECTION BOARD

LOUGHBOROUGH UNIVERSITY OF TECHNOLOGY

LOCAL AUTHORITY LASER SAFETY AWARENESS QUESTIONNAIRE

Local Authority ....

Address ....

....

....

Postcode ....

Telephone ....

Fax ....

Name of person filling out this questionnaire ....

Position ....

Date questionnaire completed ....

1. How many times has your Local Authority had to deal with the use of lasers in the entertainment industry in the LAST 12 MONTHS? ☐ **If zero move to question 3**

2. If possible can you break this down into the following categories:

Please enter number of each type of event in the appropriate box.

Permanent Installations (one week or longer) - Indoor ☐

- Outdoor ☐

Temporary Installations (less than one week)- Indoor ☐

- Outdoor ☐

Appendix C

Types of lasers:

Please enter number of each type in the appropriate box.

Helium-Neon (He-Ne)	
Argon ion	
Krypton/Argon (White Light or Mixed Gas)	
Copper Vapour	
Neodymium:YAG (Nd:YAG)	

Others (please specify) ____________________

3. How would you judge the level of expertise of your staff who either have dealt with laser events or who would do if the need arose?

Number of staff in each category

No experience	
Basic knowledge	
Experienced	

(To judge the category to use, a set of test questions is included with this questionnaire. Someone with Basic knowledge should be able to get to at least question 3 : an experienced Officer should be able to answer all 6 questions).

4. How familiar are your staff with the HSE Guidance Document PM19?

Number of staff in each category

Never heard of it	
Know of its existence	
Seen forms provided by laser companies	
Working knowledge	
Detailed knowledge	

Do you have a copy of PM19 for reference? YES/NO Delete as appropriate

5. If you either use or would consider using external assistance where do/would you go?

	Please tick all that apply
Other Local Authority	☐
Chartered Institute of Environmental Health (CIEH)	☐
Health and Safety Executive (HSE)	☐
National Radiological Protection Board (NRPB)	☐
Loughborough University	☐
Consultants	☐

Other (please specify) ____________________

6. Would you consider training staff in how to assess the safe use of lasers in the entertainment industry? YES/NO Delete as applicable

If you have answered NO, please stop here and return the questionnaire in the reply-paid envelope. Thank you for your time.

7. What level of training would you require?

		Please tick all that apply to your staff
Overview seminar	(up to 2 hours)	☐
Basic awareness	(1 day)	☐
Working knowledge	(2 days)	☐
Detailed knowledge	(4 days)	☐
I do not know enough to judge		☐

8. What format of presentation would you prefer?

	a) if costs were equal	b) if costs differed according to the ratio 1:1.5:2	
Formal lectures only	☐	x 1	☐
Lectures supported by syndicate exercises	☐	x 1.5	☐
Workshop (worked examples with demonstrations)	☐	x 2	☐

9. How far would you be prepared for staff to travel for such training?

Please put in order of preference (1 to 5) where 1 is most preferred option

Anywhere in UK ☐
A regional centre - eg Glasgow, Leeds or Oxford ☐
Up to 100 miles ☐
Up to 50 miles ☐
Within the County of this local authority only ☐

10. Would you prefer any form of training to be assessed by a formal examination? YES/NO Delete as applicable

If you have answered NO, please stop here and return the questionnaire in the reply-paid envelope. Thank you for your time.

11. If you answered YES to question 10, should this examination be accredited? YES/NO Delete as applicable

If YES, by whom?

Please tick one only

CIEH ☐
HSE ☐
NRPB ☐
Loughborough University ☐
Other (please specify)____________________

Thank you for taking the time to complete this questionnaire. Please return it in the reply-paid envelope.

Appendix C

Questions to test the level of expertise in assessing the safety of laser systems at an entertainment event.

1. What is the most common type of laser used in the entertainment industry?
2. What is the potential harm from an entertainment laser?
3. Which British Standard covers laser safety?
4. What is the maximum permissible exposure for the laser specified in 1?
5. What is the nominal ocular hazard distance for the laser in 1 if the radiant power is 1 watt and the divergence is 2 mrad?
6. How is your answer to 5 altered if the beam is scanned?

Appendix D

DI Laser Questionnaire

Please help our research by completing this questionnaire - even if you have no intention of ever installing a laser system. Please tick the boxes or enter information.

1. Which of the following best describes you?
    - Venue with installed laser systems ☐
    - Venue which hosts temporary laser shows ☐
    - Venue with no lasers now, but have had them in the past ☐
    - Venue that has never had lasers ☐
    - Venue planning to install lasers ☐
    - Laser display company ☐
    - Laser system supplier ☐

2. Which of the following types of lasers do you have now or have had?
    - Helium-Neon (He-Ne) ☐
    - Argon Ion (Ar) ☐
    - Mixed Gas/White Light (Kr/Ar) ☐
    - Copper Vapour ☐
    - Neodymium:YAG (Nd:YAG) ☐
    - Other (please specify)______________________________

3. How often is the laser used?
    - More than once per day ☐
    - Once per day ☐
    - At least once per week ☐
    - At least once per month ☐
    - At least once per year ☐
    - Less than once per year ☐
    - It is not used ☐

4. How is the laser operated?
    - Trained specialist laser operator ☐
    - Operated by DJ ☐
    - Operated by lighting jockey ☐
    - Pre-recorded show ☐
    - Manual selection of stored effects ☐
    - Manual show ☐

5. Approximate year of installation of lasers (or commencement of business if not a venue)

    ☐

6. Name of supplier(s) of lasers______________________________

7. Do you have a Laser Safety Officer? Yes ☐ No ☐

    If yes, please give an indication of how he/she was trained:

    - In-house training ☐
    - Trained by laser supplier ☐
    - External course ☐
    - No formal training ☐

8. Are you aware of the Health and Safety Executive guidance document PM19?
Yes ☐ No ☐
If no, please go to question 11

9. Do you have a copy of PM19? Yes ☐ No ☐

10. Do you find PM19 easy to understand? Yes ☐ No ☐

11. Would you be interested in a practically-based laser safety guidance document?
Yes ☐ No ☐

12. If you wanted help on laser safety, who would you approach?
Local Authority (Environmental Health Department) ☐
Local Authority (other Department) ☐
Health and Safety Executive ☐
National Radiological Protection Board ☐
Loughborough University ☐
Laser supplier ☐
Another disco/night-club, etc ☐
Safety Consultancy ☐

Trade Association (please specify)____________________

Other (please specify)____________________________

13. Are you interested in arranging laser safety training for your staff?
Yes ☐ No ☐

14. Would you find a series of articles on laser safety in DI useful?
Yes ☐ No ☐

15. Are you interested in a confidential laser safety audit?
Yes ☐ No ☐

16. If yes, how much would you be prepared to pay? ☐

17. What type of venue are you, if appropriate?
Discotheque ☐
Night-club ☐
Pub ☐
Hotel ☐
Theatre ☐
Laser game venue ☐
Open arena ☐
Other (please specify)____________________

18. What is the normal capacity of your venue? ☐

Appendix D

I will be grateful for the following information about your venue but please remain anonymous if you wish.

Name of venue/company______________________________

Postcode (or country if non-UK)______________________________

Your name______________________________

Your position______________________________

Telephone______________________________

Fax______________________________

We are looking for a number of UK venues and laser companies to assist with our research. This will include a risk assessment on the use of lasers at your venue or a discussion on the implications of installing a laser system for the first time. If you wish to be considered please attach your business card here.

John O'Hagan, NRPB

Appendix E

Suggested Sections for a Laser Display Safety Record

- I. Description of the Laser Display
    - A. Company Details
    - B. Venue Details
    - C. Description of the Event
        - 1. Date
        - 2. Timetable
        - 3. Plan of the Site
    - D. Lasers
    - E. Other Equipment
- II. Safety Structure
    - A. Company
        - 1. Laser Display Operators
        - 2. Laser Safety Officer
        - 3. Managing Director
    - B. Venue
        - 1. Venue Manager
        - 2. Health & Safety Manager
    - C. Promoter
        - 1. Name & Address
        - 2. Managing Director
        - 3. Principal Contact
        - 4. Health and Safety Manager
    - D. Equipment Manufacturers/Agents
        - 1. Lasers
        - 2. Generators
        - 3. Cooling Plants
        - 4. Optical Systems
        - 5. Smoke Generators

- E. Emergency Assistance

III. Control Measures

- A. Training
- B. Engineering Controls
- C. Security Arrangements
- D. Safety Signs
- E. Protective Eyewear

IV. Written Procedures

- A. Installation
- B. Alignment
- C. Performance
- D. Dismantling

V. Risk Assessment

- A. General
- B. Transport
- C. Installation
- D. Alignment
- E. Performance
- F. Dismantling
- G. Significant Conclusions from the Risk Assessments

VI. Liaison

- A. Licensing Authority
- B. Health and Safety Authority
- C. Civil Aviation Authority
- D. Other Aviation Authorities
- E. Marine/Harbour Authorities
- F. Fire
- G. Police
- H. Ambulance (including volunteer groups)

VII. Entertainment Licence

- A. Copy of Document or reference to its location
- B. Details of conditions specific to The Laser Display Company

VIII. Audit Record

- A. Management review log
- B. Operator check list record
- C. Enforcing Officer check log
- D. Portable Appliance Testing log
- E. Residual Current Device checks

IX. Certificates

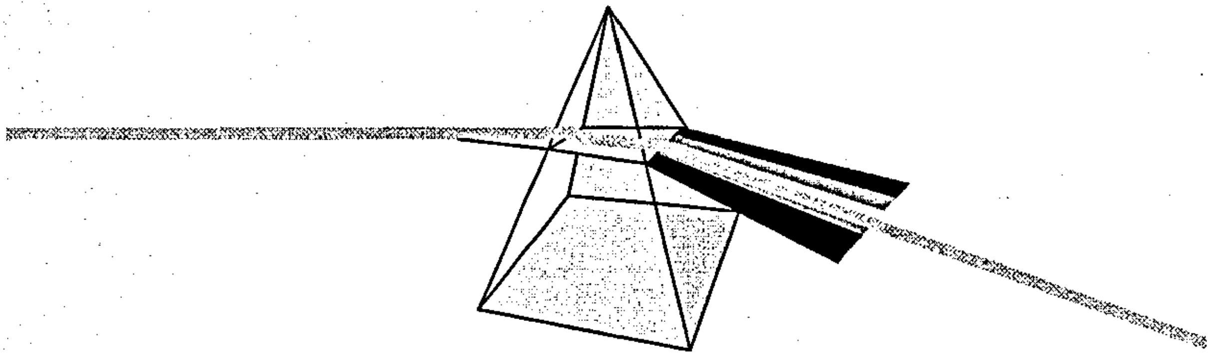
- A. Insurance (public and product liability)
- B. Safety checks (third party)
- C. Laser Power Meter(s)

X. Working Section

- A. Correspondence with venue, promoter, etc
- B. Copy of appropriate parts of contract

Appendix F
Example Laser Display Record

The Laser Display Company



Laser Display Safety Record

The Stately Home
Somewhere

6 May 1997

Introduction

This Record is produced by The Laser Display Company as part of its general commitment to safety. It is intended to meet the Company's duties under Section 6 of the Health and Safety at Work etc Act 1974 and Regulations made under that Act, particularly the Management of Health and Safety at Work Regulations 1992 and the Provision and Use of Equipment Regulations 1992. Due consideration is taken of the British Standard covering laser safety (BS EN 60825-1:1994) and current guidance from the Health and Safety Executive (HS(G)95) on the Radiation Safety of Lasers Used for Display Purposes.

The Record is presented in this comprehensive form to ensure that all of the necessary information is available for our employees, enforcing officers, the venue management and the promoter.

The assistance of the National Radiological Protection Board with the drafting and format of this Record is gratefully acknowledged but The Laser Display Company accepts full responsibility for the accuracy of the information contained herein.

1. Description of the Laser Display

1.1 Company Details

The Laser Display Company
1 The Beam
Shine
Brightshire
XY1 2AB

Telephone: 01999 999999
Fax: 01999 999999

1.2 Venue Details

The Stately Home
Somewhere
Anyshire
AB1 2XY

Telephone: 01999 999999
Fax: 01999 999999

1.3 Description of the Event

Laser display effects will be used to support a live performance by a classical orchestra. This particular show is in support of the GLOBF charity. Other visual effects will include fireworks and a water fountain. The event will take place in the grounds of The Stately Home.

1.3.1 Date

7 May 1997

On-site meeting took place on 10 April 1997. A record of the meeting is filed in Section 10 of this file.

1.3.2 Timetable

1000	Arrive on site and commence assembly
1400	Complete assembly and commence alignment
1500	Alignment complete
1700	Open to public admission
1900	Music starts
2130	Laser Show starts
2230	Performance finishes and commence dismantling
2330	Depart site

1.3.3 Plan of the Site

A plan of the site showing the layout of the stage, audience, lasers and associated equipment is filed after this page. Further plan and side elevations are also included to show the extent of the laser beams in relation to the audience and neighbouring buildings. Since the laser beams are to be projected beyond the confines of the venue, a plan of the region in which the venue is located is also included.

1.4 Lasers

Three lasers will be used for this performance. Details are as follows:

Laser 1 & 2

Manufacturer: DuoLase
Model: Display 100
Serial Number: 123456
Type: Krypton/Argon (white light or mixed gas)
Wavelengths: 476.5 nm
488.0 nm
514.5 nm
530.9 nm
568.2 nm
647.1 nm
676.4 nm
Power: 4 W maximum (sum of all wavelengths)
Beam divergence: 3 mrad (full angle at 1/e x peak power points)
Initial beam diameter: 2 mm (at 1/e x peak power points)
Class: 4

Cooling: Water
Electrical supply: 60 A three phase

Laser 3

Manufacturer: DuoLase
Model: Display 20
Serial Number: 98765
Type: Argon
Wavelengths: 488.0 nm
514.5 nm
Power: 7 W maximum (sum of both wavelengths)
Beam divergence: 2 mrad (full angle at 1/e x peak power points)
Initial beam diameter: 2.5 mm (at 1/e x peak power points)
Class: 4
Cooling: Water
Electrical supply: 60 A three phase

1.5 Other Equipment

The following is an inventory of the equipment, other than the lasers described above, which will be brought onto the site as part of the laser display:

- 3 off diesel generators
- 3 off heat exchanger plants
- 3 off scaffolding towers
- 3 off primary optical systems
- 2 off mirror balls
- 3 off control consoles
- Control cables
- Power cables
- Cooling water pipes
- 3 off smoke generators

2. Safety and Operational Structure

2.1 The Laser Display Company

2.1.1 Laser Display Operators

Mr John Smith (Person in charge on site) Mobile phone: 0999 999999
Ms Alison Doe
Mr Fred Bloggs

The three operators have UHF PMR radios for communication between them on site.

2.1.2 Laser Safety Officer

Mr Bert Major Mobile phone: 0999 999999

The Laser Safety Officer is responsible for ensuring that the Company operates to a high level of safety. He reports directly to the Managing Director.

2.1.3 Managing Director

Mr Frank Blair Mobile phone: 0999 999999

2.2 Venue

2.2.1 Estate Manager

Mr Eric Ashdown Telephone: 01999 999999 or 0999 999999 (mobile)

The Estate Manager is the main point of contact on site regarding services.

2.2.2 Health and Safety Manager

Ms Florence Starling Telephone: 01999 999999 or 0999 999999 (mobile)

2.3 Promoter

2.3.1 Name and Address

The Anything Goes Right Company
23a Building Block
Ourtown
Ourshire
ZZ6 5AB

Telephone: 01999 999999
Fax: 01999 999999

The contract for the laser show is between The Laser Display Company and The Anything Goes Right Company.

2.3.2 Managing Director

Mr Mike Lotsamoney Mobile phone: 0999 999999

2.3.3 Principal Contact

Ms Amy Curry Telephone: 01999 999999 or 0999 999999 (mobile)

Ms Curry is the main point of liaison between The Laser Display Company and the Promoter. She is considered the Customer.

2.3.4 Health and Safety Manager

Mr Ivor Plaster Telephone: 01999 999999 or 0999 999999 (mobile)

2.4 Equipment Manufacturers/Agents

2.4.1 Lasers

DuoLase
Unit 1
The Big Industrial Estate
Histown
Hisshire
AA1 2ZZ

Telephone: 01999 999999 Principal Contact: Mr A Person
Fax: 0999 999999

2.4.2 Generators

The Generator Supply Company
Their Address

Telephone: 01999 999999
Fax: 0999 999999

Principal Contact: Mr A Person

2.4.3 Cooling Plants

The Cooling Plant Supply Company
Their Address

Telephone: 01999 999999
Fax: 0999 999999

Principal Contact: Mr A Person

2.4.4 Optical Systems

The Laser Optics Supply Company
Their Address

Telephone: 01999 999999
Fax: 0999 999999

Principal Contact: Mr A Person

2.5.5 Smoke Generators

The Smoke Generator Supply Company
Their Address

Telephone: 01999 999999
Fax: 0999 999999

Principal Contact: Mr A Person

2.5 Emergency Assistance

In the first instance, the senior laser display operator from The Laser Display Company will be responsible for immediate assistance in the event of an incident involving the Company's operations at the venue. This will be backed up by the Company's other staff on site. First aid kits and appropriate fire extinguishers are available the whole time the Company representatives and its equipment are on site.

It has been agreed (see Contract filed in Section 10 of this file) that the promoter will provide first aid cover for employees of The Laser Display Company as part of its normal arrangements for its own employees and members of the public.

3. Control Measures

3.1 Training

The Laser Display Company recognises that the main control measure to reduce the risk of injury to all persons it the quality of the training of its employees. The training of the employees involved with this show is as follows:

Name	Formal Training	Experience
Mr John Smith	In-Company training scheme attended from 1/4/91-4/4/91. Update session last attended 4/1/97. Qualified First Aider - retested 5/4/97.	Joined Company 5/3/91. Experienced show designer and operator. Has been responsible for 35 shows in the last twelve months.
Ms Alison Doe	In-Company training scheme attended from 20/8/95-23/8/95. Update session last attended 4/1/97	Joined Company 5/8/95. Provides support to more experienced operators.
Mr Fred Bloggs	In-Company training scheme attended from 20/8/95-23/8/95. Update session last attended 4/1/97	Joined Company 5/8/95. Provides support to more experienced operators.
Mr Bert Major	In-Company training scheme attended from 1/6/89-4/6/89. Update session last attended 4/1/97. Attended US New York state laser display training course 6/9/92-8/9/92.	Joined Company at the beginning (3/4/88). Experienced laser show designer and operator. Has been responsible for 20 shows in the last twelve months and 10 fixed installations.

3.2 Engineering Controls

Where possible our laser display installations are designed to minimise the risk of injury to any person. As such, the laser and primary optical systems are rigidly mounted on the same baseplate to minimise the risk of relative movement. All optical components are securely mounted with a minimum of two fixing bolts or screws. The optical path with the primary optics is constrained by the use of local shielding covers. The laser apertures are all masked. Although these masked are adjustable, they are secured after adjustment by four fixing bolts.

The primary optical system is of a revolutionary design which allows all adjustments on site to be made from above with the minimum of covers removed. No alignment within the laser chassis is made on site.

3.3 Security Arrangements

Each of the lasers is key operated. Once the laser is mounted in position and coupled to the primary optical system there are no accessible beam paths until the control system is activated.

Each of the control systems is password protected. The shutter can only be opened, and laser radiation made accessible, when the correct password is entered.

The control consoles, lasers and optical systems are located in restricted areas. Access to these areas is for pass holders only.

3.4 Safety Signs

Each laser control area is designated a Laser Controlled Area when the key to the laser is in place (whether switched on or not). Signs are placed prominently at the entrance to each Laser Controlled Area as follows:

Caution Laser Starburst symbol with the legend "Laser Controlled Area"

Prohibition symbol with the legend "Laser Display Company Authorised Personnel Only"

The name of the responsible person and the Laser Safety Officer, along with details of how to contact them are also displayed.

3.5 Protective Eyewear

During normal operations and normal alignment work it is not necessary to wear laser safety eyewear. However two pairs of Kr/Ar goggles are available should some unforeseen alignment work be necessary. These are designed to provide sufficient protection in the event of an accidental eye exposure.

Manufacturer:	The Laser Eyewear Company
Stated OD:	???
Stated wavelength:	???
Indications:	????

4 Written Procedures

Written procedures have been prepared by the Company for the operations carried out away from the Company's premises. These are separated to cover installation of the laser display system, alignment work, the performance and dismantling. In each case a contingency plan has been prepared to cover reasonably foreseeable incidents or accidents.

Each member of staff is required to have read and understood the contents of these Written Procedures. A record of this is maintained in Section 8 of this file.

Where the involvement of third parties required for the successful implementation of these Written Procedures this has been agreed in writing (see Section 8).

4.1 Written Procedures for Installation

4.1.1 Introduction

These Written Procedures have been prepared for the installation of the laser display at The Stately Home on 6 May 1997. They should be seen as implementing, at least in part, The Laser Display Company's duties under Section 6 of the Health and Safety at Work etc Act 1974.

4.1.2 Responsibilities

The Laser Display Company is represented on site by:

Mr John Smith Mobile phone: 0999 999999

The Laser Safety Officer is:

Mr Bert Major Mobile phone: 0999 999999

4.1.3 Duties

All staff will work in a safe and responsible manner with due regard for their own safety and that of others.

4.1.4 Emergency Arrangements

The most likely incidents during installation relate to physical impact and falling. There should be no risk of injury from laser radiation. Where appropriate, first aid should be applied and, if necessary, the relevant emergency services summoned. First aid support is available from The Stately Home by telephoning 01999 999999.

4.2 **Written Procedures for Alignment**

4.2.1 Introduction

These Written Procedures have been prepared for the alignment of the laser display at The Stately Home on 6 May 1997. They should be seen as implementing, at least in part, The Laser Display Company's duties under Section 6 of the Health and Safety at Work etc Act 1974.

4.2.2 Responsibilities

The Laser Display Company is represented on site by:

Mr John Smith	Mobile phone: 0999 999999

The Laser Safety Officer is:

Mr Bert Major	Mobile phone: 0999 999999

4.2.3 Duties

All staff will work in a safe and responsible manner with due regard for their own safety and that of others.

Before powering up any of the equipment a check should be made of the layout and integrity of the power and water systems. The structural integrity of the support structure should be confirmed.

A particular concern during alignment work is the potential for accidental exposure to the laser radiation. To minimise the potential for this, the number of people in the vicinity should be minimised and, if reasonably possible, eliminated completely.

Alignment should be carried out at the minimum power necessary and, where possible, should be carried out with the laser beam constrained, ie by using local shielding. It should be recognised that alignment with external optical components during daylight may require almost full power.

4.2.4 Emergency Arrangements

The most likely incidents during alignment relate to laser radiation exposure. During alignment with the primary optical system, the operator is at greatest risk. However, alignment with the secondary optics may expose others. If an actual or suspected eye exposure occurs then a judgement will need to be made on the course of action. If the incident involves a third party then they should be referred to an ophthalmologist. An employee of the Company will be encouraged to see an ophthalmologist within 24 hours.

Other accidents and incidents could occur which relate to working at height, high voltages, etc. Where appropriate, first aid should be applied and, if necessary, the relevant emergency services summoned. First aid support is available from The Stately Home by telephoning 01999 999999.

4.3 Written Procedures for the Performance

1 Introduction

These Written Procedures have been prepared for the performance of the laser display at The Stately Home on 6 May 1997. They should be seen as implementing, at least in part, The Laser Display Company's duties under Section 6 of the Health and Safety at Work etc Act 1974.

4.3.2 Responsibilities

The Laser Display Company is represented on site by:

Mr John Smith Mobile phone: 0999 999999

The Laser Safety Officer is:

Mr Bert Major Mobile phone: 0999 999999

4.3.3 Duties

All staff will work in a safe and responsible manner with due regard for their own safety and that of others.

Before powering up any of the equipment a check should be made of the layout and integrity of the power and water systems. The structural integrity of the support structure should be confirmed.

Communication links between the three operators should be confirmed prior to the commencement of the performance.

The show will have been pre-programmed and aligned to ensure that no members of the audience or other staff are at risk.

4.3.4 Emergency Arrangements

The lasers incorporate temperature sensors which turn the respective laser off in the event of cooling failure. Loss of power to the laser will automatically terminate the emission of laser radiation.

In the event of a developing situation in the audience, such as unruliness, each operator is aware of the duty to terminate the laser show if appropriate. Each operator can make this decision without reference to the other operators.

Failure of the control system or primary optics should result in a failure to safety due to the masking of the laser apertures. However, the operator will decide whether the performance from that laser can continue safely in any form.

If an actual or suspected eye exposure occurs then a judgement will need to be made on the course of action. If the incident involves a third party then they should be referred to an ophthalmologist. An employee of the Company will be encouraged to see an ophthalmologist within 24 hours.

Other accidents and incidents could occur which relate to working at height, high voltages, etc. Where appropriate, first aid should be applied and, if necessary, the relevant emergency services summoned. First aid support is available from The Stately Home by telephoning 01999 999999.

4.4 Written Procedures for Dismantling

4.4.1 Introduction

These Written Procedures have been prepared for the dismantling of the laser display at The Stately Home on 6 May 1997. They should be seen as implementing, at least in part, The Laser Display Company's duties under Section 6 of the Health and Safety at Work etc Act 1974.

4.4.2 Responsibilities

The Laser Display Company is represented on site by:

Mr John Smith	Mobile phone: 0999 999999

The Laser Safety Officer is:

Mr Bert Major	Mobile phone: 0999 999999

4.4.3 Duties

All staff will work in a safe and responsible manner with due regard for their own safety and that of others. Due consideration should be given to the lighting levels and the presence of members of the public and vehicles (particularly those from other employers).

If there is a requirement for the cooling water to continue to flow for a period after the end of the performance then due consideration should be taken of the risks associated with this. Equally, when the cooling water is drained, this should be to a ditch and not in the vicinity of the structural work and high voltages.

4.4.4 Emergency Arrangements

The most likely incidents during dismantling relate to physical impact and falling. There should be no risk of injury from laser radiation. Where appropriate, first aid should be applied and, if necessary, the relevant emergency services summoned. First aid support is available from The Stately Home by telephoning 01999 999999.

5. Risk Assessments

These risk assessments are provided in compliance with The Laser Display Company's duties under Regulation 3 of the Management of Health and Safety at Work Regulations. Consideration is also given to the requirements for an Installation Safety Assessment in Chapter 4 of the Health and Safety Executive guidance HS(G)95 "The Radiation Safety of Lasers Used for Display Purposes".

The methodology used here is based on that developed by the National Radiological Protection Board and Loughborough University. We are grateful for the practical assistance that they have provided but the responsibility for the content and adequacy of the assessment rests with The Laser Display Company.

The assessment is considered as a function of the life cycle of the display for each section of the display and considers groups of people at risk. The assessment is presented in a format similar to that recommended in the Health and Safety Executive guidance "The Five Steps to Risk Assessment". A hazard is defined as the physical entity which has the potential to do harm; a risk is the result of the hazard being realised coupled with the likelihood of it being realised. In some cases, as appropriate, due account is also taken of the number of people at risk.

5.1 General

The Laser Display Company is committed to providing a safe environment for its employees and others who may be affected by its work activities, including members of the public. The assessment described here does not take account of work activities at our own premises. This is the subject of a separate assessment document. What is covered here is transport from our premises to the venue, and from venue to venue; installation of the laser display at the venue; alignment and testing of the display; the performance; and dismantling.

5.2 Transport

The laser display system is transported from our premises to the venue in a ***** truck owned by the Company. All of the equipment is transported in flight cases to minimise the risk of damage.

Hazards	Persons at Risk	Control Measures	Comments
Manual Handling ■ crushed limbs ■ crushed extremities ■ back injuries	Employees.	Training Back lift on vehicle Casters on flight cases	Adequately controlled
Movement of Load During Transit	Employees. Others.	Training Flight case installation planned to minimise movement. Restraining straps used	Adequately controlled No reported incidents by employees
Road Traffic Accident	Employees. Others.	Driver training and demonstration of competence with the **** vehicle. All three operators are competent to drive the vehicle to ensure adequate rest periods, especially after performances	The Company considers it has taken all reasonable precautions to reduce the risk of "own fault" accidents and the probability of involvement with incidents caused by other drivers. The company has had no accidents involving its vehicles since $$$$.
Vehicle Breakdown	Employees affecting repair. Others.	Regular vehicle maintenance. Pre-journey check schedule. High visibility vests provided in vehicle to be worn if vehicle does break down	The Company considers it has taken all reasonable precautions to reduce the risk of vehicle breakdown and to protect its staff should this occur.
Vehicle Fire	Employees Others.	Regular vehicle maintenance. Pre-journey check schedule. Vehicle fire extinguisher carried in cab. Staff have received training in its operation.	The Company considers it has taken all reasonable precautions to reduce the risk of vehicle fire and to protect its staff and other should this occur.

5.3 Installation

Most of the risks during installation relate to the weight of some components of the laser display system and working at height. It is assumed for this assessment that none of the equipment is switched on. The assessment for the alignment work covers the next stage where equipment is switched on.

The assessment is broken down into the different segments of the display.

5.3.1 Lasers

Hazard	Persons at Risk	Control Measures	Comments
Manual Handling ■ crushed limbs ■ crushed extremities ■ back injuries	Employees Others in the vicinity	Training Provision of gloves for employees Provision of appropriate footwear for employees	Adequate
Working at height ■ falling ■ dropping the laser	Employees Others in the vicinity	Training Provision of appropriate footwear for employees	Adequate

5.3.2 Equipment Associated with the Lasers

This section considers the installation of the cooling plants, the diesel generators, smoke generators, and cabling and pipework associated with these items.

Laser Exciters

Hazard	Persons at Risk	Control Measures	Comments
Manual Handling ■ crushed limbs ■ crushed extremities ■ back injuries	Employees Others in the vicinity	Training Provision of gloves for employees Provision of appropriate footwear for employees	Adequate
Sharp Edges	Employees	Provision of gloves for employees	Adequate

Cooling Plants

Hazard	Persons at Risk	Control Measures	Comments
Manual Handling ■ crushed limbs ■ crushed extremities ■ back injuries	Employees Others in the vicinity	Training Provision of gloves for employees Provision of appropriate footwear for employees	Adequate
Sharp Edges	Employees	Provision of gloves for employees	Adequate

Diesel Generators

Hazard	Persons at Risk	Control Measures	Comments
Manual Handling ■ crushed limbs ■ crushed extremities ■ back injuries	Employees Others in the vicinity	Training Provision of gloves for employees Provision of appropriate footwear for employees	Adequate
Battery Acid	Employees	Sealed unit	Adequate
Diesel fuel	Employees Other in the vicinity	Provision of gloves for employees Purpose fuel containers See also COSHH assessment contained in Section ****	Adequate

Smoke Generators

Hazard	Persons at Risk	Control Measures	Comments
Manual Handling ■ crushed limbs ■ crushed extremities ■ back injuries	Employees Others in the vicinity	Training Provision of gloves for employees Provision of appropriate footwear for employees	Adequate
Sharp Edges	Employees	Provision of gloves for employees	Adequate
Fluid	Employees	Training. Anti-spill design. See also COSHH assessment in Section ****	Adequate

Cables

Hazard	Persons at Risk	Control Measures	Comments
Trip hazard	Employees Others in the vicinity	Training of employees Consideration of cable routes. Cables are bright yellow	Adequate
Manual Handling ■ crushed limbs ■ crushed extremities ■ back injuries	Employees Others in the vicinity	Training Provision of gloves for employees Provision of appropriate footwear for employees	Adequate

Cooling Water Pipes

Hazard	Persons at Risk	Control Measures	Comments
Trip hazard	Employees Others in the vicinity	Training of employees Consideration of pipe routes. Pipes are bright red	Adequate
Manual Handling ■ crushed limbs ■ crushed extremities ■ back injuries	Employees Others in the vicinity	Training Provision of gloves for employees Provision of appropriate footwear for employees	Adequate

5.3.3 Primary Optics

Hazard	Persons at Risk	Control Measures	Comments
Manual Handling ■ crushed limbs ■ crushed extremities ■ back injuries	Employees Others in the vicinity	Training Provision of gloves for employees Provision of appropriate footwear for employees	Adequate
Working at height ■ falling ■ dropping the optics	Employees Others in the vicinity	Training Provision of appropriate footwear for employees	Adequate

5.3.4 Support Structure

Hazard	Persons at Risk	Control Measures	Comments
Manual Handling ■ crushed limbs ■ crushed extremities ■ back injuries	Employees Others in the vicinity	Training Provision of gloves for employees Provision of appropriate footwear for employees	Adequate
Tower stability ■ crushing hazard	Employees Others in the vicinity	Purpose designed structure Wooden spreaders installed under feet. Outriggers installed at earliest opportunity	Adequate
Working at height ■ falling ■ dropping the laser	Employees Others in the vicinity	Training Provision of appropriate footwear for employees	Adequate

5.3.5 Secondary Optics

Hazard	Persons at Risk	Control Measures	Comments
Manual Handling ■ crushed limbs ■ crushed extremities ■ back injuries	Employees Others in the vicinity	Training Provision of gloves for employees Provision of appropriate footwear for employees	Adequate
Working at height ■ falling ■ dropping the optics	Employees Others in the vicinity	Training Provision of appropriate footwear for employees	Adequate

5.3.6 Operators

Hazard	Persons at Risk	Control Measures	Comments
Poor working protocol	Other Employees Others in the vicinity	Training The Company regularly audits the work of its employees	Adequate
Poor workmanship	Employees Others in the vicinity	Training The Company regularly audits the work of its employees	Adequate

5.3.7 Staff other than Operators

There are likely to be a number of other staff in the vicinity of the working areas during installation. This assessment considers the risks presented to the Company's employees by these other groups of staff, who are not employees of the Company. The contractual arrangement with the event promoter requires that these other groups of staff should consider the safety of our employees.

Hazard	Persons at Risk	Control Measures	Comments
Stage installation ■ large structure	Our Employees	Our employees are not permitted to enter the immediate area of the stage until clearance has been given by the stage manager	Adequate
Sound installation ■ large structure ■ lorry movements ■ trailing cables	Our Employees	The work our employees are required to undertake is away from the sound systems and the proposed vehicle movements	Adequate
Other vehicle movements	Our Employees	All vehicle movements are controlled and a site speed limit of 10 mph will be imposed	Adequate

5.3.8 External Factors

Hazard	Persons at Risk	Control Measures	Comments
Rain	Employees	Suitable footwear and rainwear is provided Tarpaulins are provided for equipment	Adequate Employees should be aware of the increased risk of slipping
Sun	Employees	Sun hats and factor 15 sun lotion is provided	Adequate
Wind	Employees Others in the vicinity	As described in the previous sections, the stability of the various structures is considered important from an operational viewpoint.	Adequate

5.4 Alignment

The alignment stage is considered to start as soon as power is applied to the laser or any of the associated systems, including the cooling plant, or when the diesel generators are started. At the alignment stage it is assumed that covers may be removed from some of the equipment and the risk assessment takes this into account.

5.4.1 Lasers

The lasers are proprietary pieces of equipment which themselves comply with the requirements of the current British Standard on laser safety, BS EN 60825-1:1994. The lasers are maintained and adjusted at our premises prior to transport to the venue and no further on-site alignment or adjustment is envisaged. Therefore, this section is included for completeness only.

Hazard	Persons at Risk	Control Measures	Comments
High voltages	Employees	Training. Access is not generally possible through engineering controls, ie secondary covers if the main chassis cover is removed. Access to laser area is restricted to employees by the use of a barrier and safety signs.	Adequate
High temperatures	Employees	Training. Employees know which surfaces are at an elevated temperature. During normal operation (including alignment) the accessible surfaces are not sufficiently hot to cause a burn.	Adequate
Laser radiation (may need to be quantified)	Employees	Training. Appropriate protective eyewear is available for alignment work.	Adequate
Collateral radiation (may need to be quantified)	Employees	Training. Only one employee is permitted to work in the immediate vicinity with the covers removed. The duration of exposure is kept to a minimum.	Adequate

5.4.2 Equipment Associated with the Lasers

This section considers the laser exciters, cooling plants, the diesel generators, smoke generators, and cabling and pipework associated with these items.

Laser Exciters

Hazard	Persons at Risk	Control Measures	Comments
High voltages	Employees Others in the vicinity	Covers remain in place at all times	Adequate
Sharp edges	Employees Others in the vicinity	The exciter is sited away from thoroughfares.	Adequate

Cooling Plants			
Hazard	**Persons at Risk**	**Control Measures**	**Comments**
Noise (may need to be quantified)	Employees Others in the vicinity	Positioned away from occupied areas	Adequate
High pressure water (may need to be quantified)	Employees Others in the vicinity	High pressure hoses and clips used. Integrity of cooling system confirmed as soon as possible after switch on	Adequate
Sharp Edges	Employees Others in the vicinity	Positioned away from occupied areas	Adequate

Diesel Generators			
Hazard	**Persons at Risk**	**Control Measures**	**Comments**
Diesel fuel	Employees Other in the vicinity	Provision of gloves for employees Purpose fuel containers See also COSHH assessment contained in Section ****	Adequate
Diesel fumes	Employees Others in the vicinity	Exhaust to unoccupied areas confirmed on site	Adequate
High temperatures	Employees	Training Covers kept closed when unattended	Adequate
Noise (may need to quantify)	Employees Others in the vicinity	Covers kept closed except when access required.	Adequate
Battery Acid	Employees	Sealed unit	Adequate

Smoke Generators			
Hazard	**Persons at Risk**	**Control Measures**	**Comments**
Smoke	Employees Others in the vicinity	Minimum quantity necessary for alignment and testing used. See also COSHH assessment in Section ****	Adequate
Sharp Edges	Employees Others in the vicinity	Positioned away from general access areas	Adequate
Fluid	Employees	Training. Anti-spill design. See also COSHH assessment in Section ****	Adequate

Cables			
Hazard	**Persons at Risk**	**Control Measures**	**Comments**
High voltages	Anyone	Armoured cables for high voltages. RCDs installed	Adequate
Trip hazard	Employees Others in the vicinity	Cables are bright yellow	Adequate

Cooling Water Pipes			
Hazard	**Persons at Risk**	**Control Measures**	**Comments**
High pressure water	Employees Others in the vicinity	Pipes are inspected prior to installation. High pressure hosing used with appropriate connectors	Adequate
Trip hazard	Employees Others in the vicinity	Pipes are bright red	Adequate

6. Liaison

This section of the file is used to file relevant correspondence and notifications to/from various official bodies involved with the laser display or who could be affected by the display.

6.1 Licensing Authority

The Licensing Authority for the event is:

The Somewhere District Council
Somewhere
XY9 4AB

The principal contact is:

Ms A Officer, Licensing Officer

Telephone: 01999 999999
Fax: 01999 999999

Notification first made: 1 February 1997

Copies of documents are filed here.

6.2 Health and Safety Authority

The Health and Safety Authority for the event is:

The Somewhere District Council
Somewhere
XY9 4AB

The principal contact is:

Mr B Safely, Senior Environmental Health Officer

Telephone: 01999 999999
Fax: 01999 999999

Notification first made: 1 February 1997

Copies of documents are filed here.

6.3 Civil Aviation Authority

Details of the event have been forwarded to the Civil Aviation Authority at Gatwick. A copy of the notification is filed in this Section of the file.

Principal contact: ** ***** ********

Telephone: 01293 573262
Fax: 01293 573971

6.4 Other Aviation Authorities

Due to the proximity of The Stately Home to the following airports, these have been notified direct (copies of the correspondence is filed in this Section of the file):

RAF ******

Principal contact: ** ***** *******

Telephone: 01999 999999
Fax: 01999 999999

The Somewhere Flying School

Principal contact: ** ***** *******

Telephone: 01999 999999
Fax: 01999 999999

6.5 Marine/Harbour Authorities

The Stately Home is sufficiently far inland that notification of Marine/Harbour Authorities is not considered appropriate.

6.6 Fire

The fire service local to The Stately Home is:

The Somewhere Fire Brigade

Principal contact: ** ***** *******

Telephone: 01999 999999
Fax: 01999 999999

Details of the laser display have been forwarded to the Fire Brigade and it is understood that an on-site inspection will take place.

6.7 Police

The constabulary local to The Stately Home is:

The Local Constabulary

Principal contact: ** ***** *******

Telephone: 01999 999999
Fax: 01999 999999

Correspondence with the constabulary is filed in this Section of the file. Particular concern has been expressed over the proximity to the main A??? trunk road and the potential for driver distraction. This has been addressed.

6.8 Ambulance

On site first aid will be provided by ***********. Several Groups will provide ambulances and first-aiders to patrol the site. These are aware of the use of lasers on site.

Principal contact: ** ***** *******

Telephone: 01999 999999
Fax: 01999 999999

In addition the County Ambulance Service will be summoned for assistance in the event of a major incident.

Principal contact: ** ***** *******

Telephone: 01999 999999
Fax: 01999 999999

7. Entertainment Licence

This section is used to file information relating to the Entertainment Licence. The Licensee is The Anything Goes Right Company. However, the Licence puts certain conditions on the use of the lasers.

A copy of the Entertainment Licence is held in Section 7.1. Details of the particular conditions effecting The Laser Display Company are given in Section 7.2.

8. Audit Record

This Section of the file is used to file the audit records which assist in demonstration compliance with our own procedures as well as legal requirements.

8.1 Management Review Log

The Laser Safety Officer will review the planned laser display and certify in this section that he is satisfied that the performance will be able to take place with a minimum of risk to all parties.

8.2 Operator Check List Record

This Section contains the final check list to be used by the Operator in charge on the day. It is used as an assurance that safety critical examinations of the laser display have been carried out.

8.3 Enforcing Officer Check Log

This log records the checks undertaken by the enforcing officer(s).

8.4 Portable Appliance Testing Log

This log confirms that all of the portable electrical equipment has been tested within the last six months.

8.5 RCD Checks

All RCDs should be checked prior to use. This is a log of these checks.

9. Certificates

Photocopies of various certificates should be filed in this Section.

9.1 Insurance

The Laser Display Company carried third party liability insurance up to £15,000,000 and product liability insurance up to £10,000,000. Employer liability insurance is to a maximum of £1,000,000.

Copies of the relevant certificates are filed in this Section.

9.2 Safety Checks

The Laser Display Company employs The Laser Display Inspection Company to provide an independent audit of its working practices. The current certificate is filed in this Section.

9.3 Laser Power Meter

The Wizzo Laser Power Meter is calibrated every 12 months by the Laser Calibration Company. The current calibration certificate is filed in this Section.

10. Working Section

There are a number of records of meetings and correspondence which do not readily fit into one of the other file Sections. These should be filed here. By default, they should be filed in date order, with the oldest at the back working forward to the most recent.