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SAFETY ASPECTS OF A HIGH POWER CO_2 LASER SYSTEM FOR CLASS I OPERATION

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SAFETY ASPECTS OF A HIGH POWER CO_2 LASER SYSTEM FOR CLASS I OPERATION

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ABSTRACT

Under the laser product classifications of the British Standard for the Safe Use of Lasers any unprotected multikilowatt laser is a Class 4 laser product. For safe extensive use or industrial production purposes a Class 1 laser product classification is necessary where powers in excess of 0.8mW cannot leave the protective enclosure of the product. The laser, beam line, focusing optics and workpiece manipulators must be enclosed such that the beam is contained and absorbed within a Designated Laser Area. Within an economic multiworkstation system it is necessary to have Designated Laser Area boundaries which can be changed automatically or with minimum inconvenience.

The case study describes the design of beam routing equipment, workstation enclosures, and interlock philosophy for a multiple workstation system incorporating a 5kW or 10kW CO_2 laser. The system offers full personnel protection with a high degree of operational convenience.

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1. INTRODUCTION

During the early stages of adoption of the multikilowatt CO_2 laser as a machine tool, a single laser source is required to perform material processing at a number of workstations. The laser beam can be switched from one workstation, where it may be performing welding, to a second heat-treating station. Meanwhile, operators or service personnel may require access to an adjacent workstation to install or modify processing equipment. In the R & D environment regular operator access to the processed material is required with possible constant visual monitoring of the material processing. In industry multi-workstation operation is also important, since it is possible to capitalise on the very short processing times of high powered lasers.

The subject of this case study is the design of system hardware, control and procedures which will avoid the potential laser hazards of multiple workstation operation.

The laser under discussion is CL5, the 5 kW transverse flow CO_2 laser designed and manufactured by the Culham Laboratory of the U.K. Atomic Energy Authority. Two systems are operated by the UKAEA; a three-workstation complex used for laser processing assessment and development at Culham Laboratory, and a two-workstation system, used for development of methods for the fabrication and dismantling of nuclear components, at the Springfields Nuclear Power Development Laboratories, Preston. Further systems are being manufactured for CL10, the 10 kW laser at Culham.

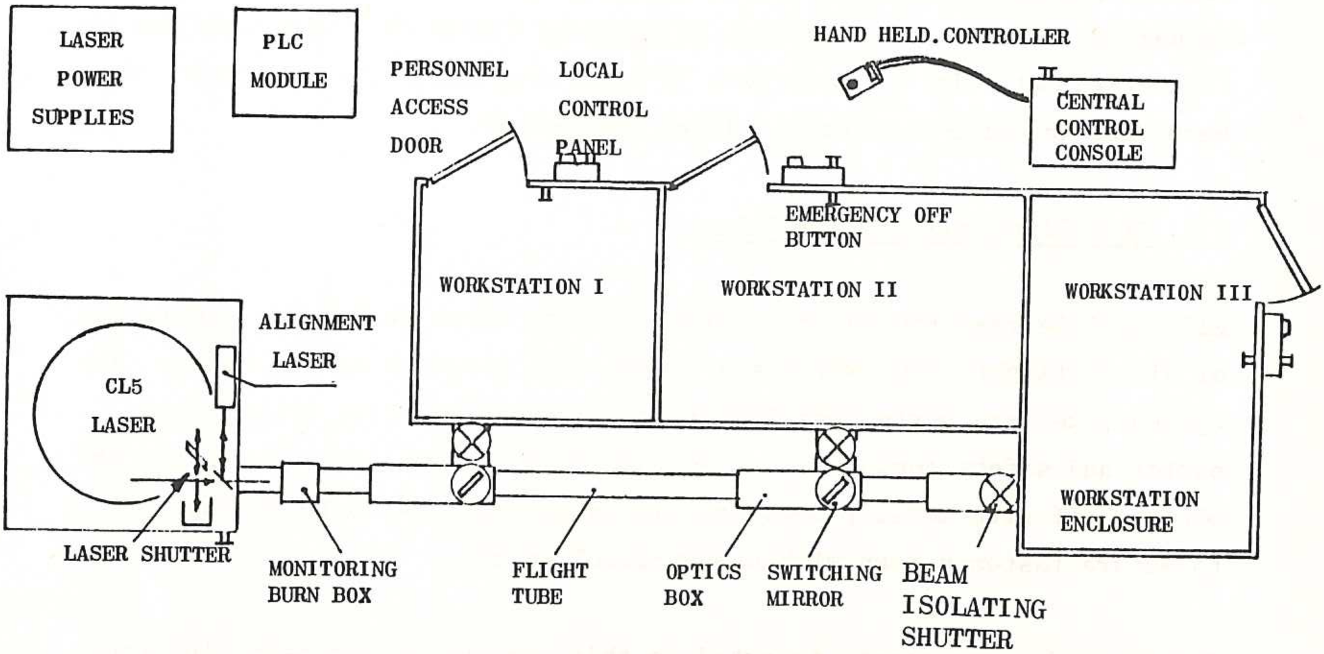
These systems were designed to comply with the UKAEA Safety Code for the Use of Lasers in the Laboratory(1). The resulting systems also comply with the 9th draft of the new British Standard on Laser Products and Equipment(2). The American National Standard for the Safe Use of Lasers(3) has been used for guidance.

Any unprotected multikilowatt laser is a Class 4 laser product. For safe extensive use or industrial production purposes a Class 1 laser product classification is necessary. This implies that it should be impossible for powers in excess of 0.8 mW to escape through a 1 mm limiting aperture. The laser, beam line, focusing optics and workpiece manipulators must be enclosed and protected. The beam is contained and absorbed within a designated laser area (DLA) or protective enclosure. Furthermore, for reasons of operational convenience and economics, it is necessary for this DLA to have boundaries which can be changed automatically or with minimum inconvenience. It is the design of this changeable laser-proof enclosure that has provided the greatest challenge in this work.

Fig.1 A typical multiworkstation arrangement.

2. GENERAL DESCRIPTION

The basic components of the safety enclosure of a multi-workstation system are shown in Fig. 2. Their operation and safety functions are outlined below.



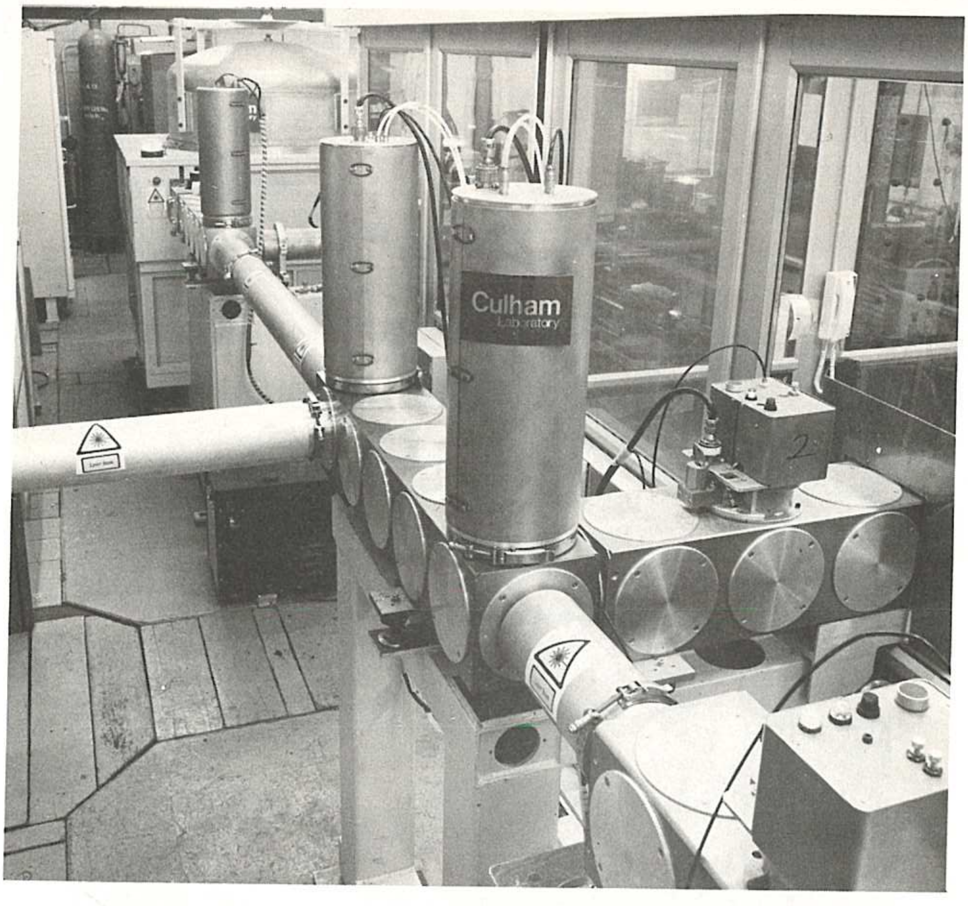


Fig.2 Typical components of a multiworkstation system.

2.1 Laser

The laser contains its own shutter in the form of a sliding mirror which deflects the beam into a water cooled calorimeter/dump. The laser shutter prevents the laser beam from entering the beam-line unless requested. For optics alignment an expanded 1mW He-Ne laser beam can be introduced onto the 5kW beam axis by inserting a thin pellicle into the beam-line when the shutter is closed and bolted.

2.2 Beam Lines and Beam Handling

All possible beam routes are enclosed within metal enclosures consisting of either flight tubes which are locked into place or optics boxes. The optics boxes are ported enabling beam directing mirrors, processing optics and safety components to be installed. Spare port facilities are blanked off with metal plates and all components fitted to the optics boxes are fastened down with tamper-proof screws.

The two major components inserted in this section of the beam line are the beam switching mirrors and the beam isolating shutters (Fig. 3).

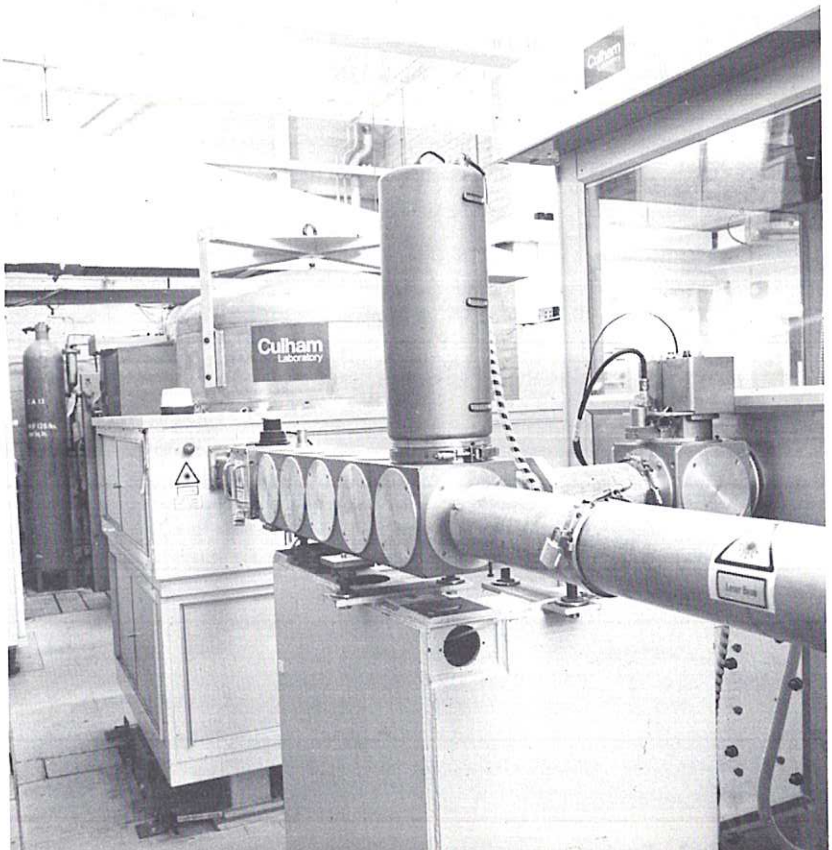


Fig.3 Switching mirror and beam isolating shutter in beam-line system.

Switching Mirrors can be introduced remotely into the beam line to direct the beam into selected workstations. They have no function in the personnel safety system except to fit in a light-tight manner in the optics box. Their position is monitored to prevent misdirection of the beam. (Figure 4 shows a switching mirror removed from the optics box.)

Beam Isolating Shutters are situated in the last section of beam line before the beam enters any workstation, and are the major safety components of the system. Their operation controls the extent of the system (DLA) and they provide safe isolation of workstations from otherwise hazardous areas and situations. Features of the beam isolating shutters are discussed in greater detail in Section 3.

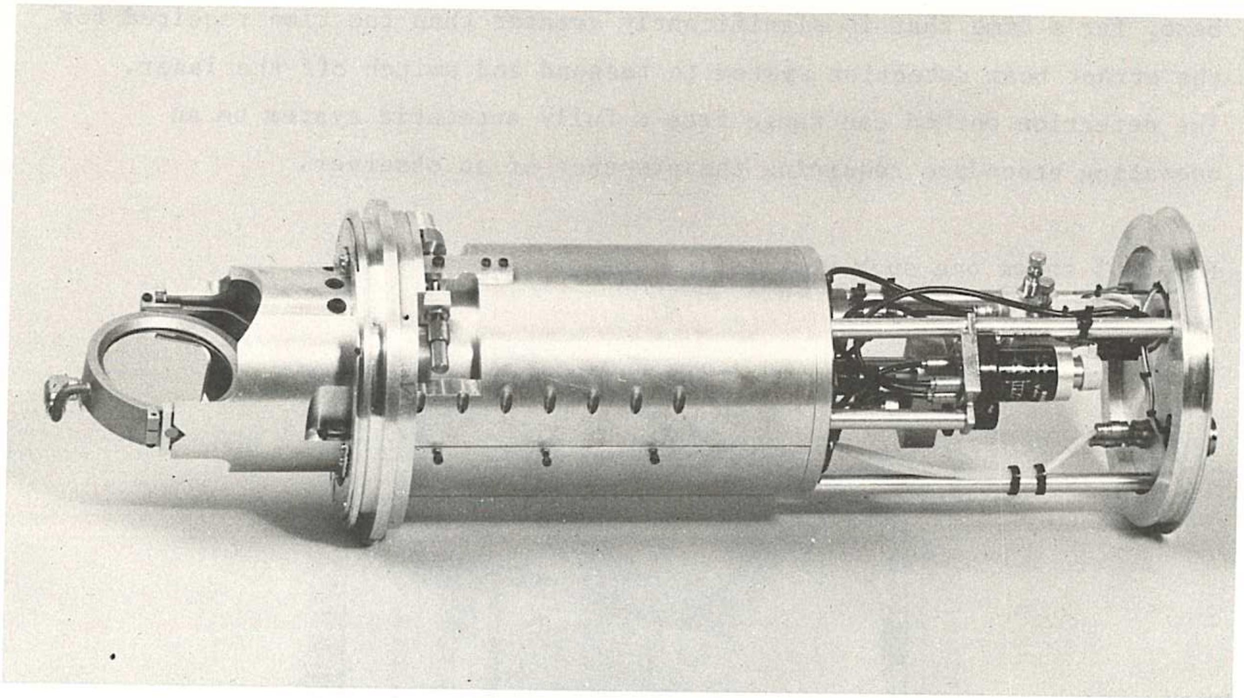


Fig.4 Beam switching mirror.

2.3 Workstation Enclosures

The workstation enclosures for R & D systems need to be relatively large and versatile. The current series of enclosures are based on a modular construction and are arranged to be more than twice the focal length away from any focusing element within the enclosure (the 2f rule). In this way the highest intensity that the workstation enclosure panels can encounter is that of the raw, unfocussed, laser beam. This rule covers the majority of workstation requirements. When very long focal length optics form part of a system, however, it is necessary to supplement the protection by providing water cooled copper beam stops or guide tubes to constrain positively the focussing beam to its intended path.

The primary selection criterion for workstation enclosures is that they be constructed to resist penetration, by the maximum power unfocussed beam, for a time that is significantly greater than the time required for the errant beam detection system to respond and switch off the laser. The detection method can range from a fully automatic system to an operating procedure requiring the presence of an observer.

Figure 5 shows one such workstation enclosure.

Fig.5 An operational workstation enclosure.

2.4 Beam and Workstation Control

The mechanical locking and electrical interlocking is designed to prevent personnel access to hazardous areas such as the beam line and workstations. Since frequent and easy access to workstations is required it is undesirable to use power interlocking by direct mechanical control. The preferred alternative indicated by BS5304[4] is the use of control interlocks with backup circuits designed such that there must be a minimum of two independent faults before the plant can become unsafe.

Equipment and operations interlocks are programmed through the Programmable Logic Controller (PLC) Module in the laser control rack. They are, by definition, inadequate for primary personnel safety but are provided for ease of operation and equipment safety.

The Central Control Console is used to set laser parameters, and switching mirror controls. Hardwired safety interlock circuits are routed through this console.

The Local Control Panel, used to operate the beam isolating shutter, is situated for convenience at the relevant workstation door. It also houses an 'emergency off' button[5], the workstation warning light and process control switches (Figure 6).

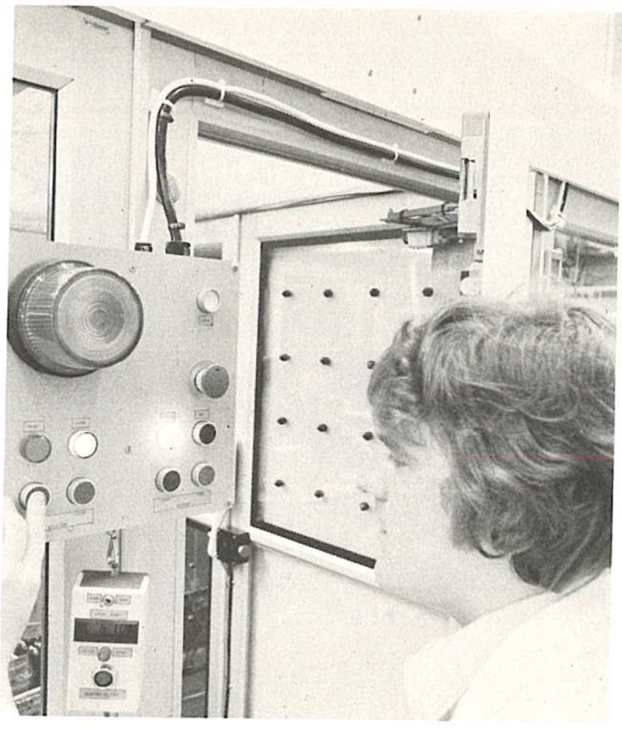


Fig.6 Local control panel, workstation door interlocks.

The Hand-Held Controller is an extension of the Central Control Console. This controller is on a flying lead that can reach the viewing areas of each workstation (Figure 5). It incorporates a laser power meter, the work/align mode switch, a 'beam ready' light and the laser shutter button. When all interlocks are made and the work mode selected, the 'beam ready' light is illuminated. The shutter button can then be used either to open directly the laser shutter or initiate a programme of openings and other functions (e.g. processing speed). Releasing the button will always close the laser shutter even if part way through a programmed run.

3. SAFETY PHILOSOPHY

3.1 General Multiworkstation Philosophy

The safety philosophy provides for three modes of operation of the workstation enclosures. This philosophy enables free, safe access into a workstation to check optics alignment and to retrieve processed workpieces or laser equipment while processingis performed in adjacent workstations.

i) Work Mode

In this mode the multikilowatt laser beam is available in the workstation. The workstation is then within the designated laser area boundary. Personnel access through the workstation door is prevented by an electromagnetic door bolt. This can be unbolted only by being energised when the beam isolating shutter is closed. A limit switch on the door is arranged to break an independent back-up circuit, closing the beam isolating shutter if the door is opened. The door bolt and door limit switch can be seen in figure 6.

The door bolt is designed to be opened from the inside whether or not the electromagnetic action is energised.

ii) Align Mode

In this mode the multikilowatt beam is prevented from entering the beam line. The expanded HeNe laser beam is available for alignment in any workstation; personnel access doors and isolating beam dumps can be freely opened. The laser shutter is bolted closed and only when it is bolted are the interlock circuits on the workstation enclosure doors and beam isolating shutters by-passed. Control of the Work/Align modes is with the hand-held controller.

iii) Isolated Mode

In this mode the multikilowatt beam is available in adjacent workstations but the isolated workstation is removed from the designated laser area by its closed beam isolating shutter.

The beam isolating shutter can be opened only by the Local Control Console at the workstation personnel access door when the door is closed and 'work mode' interlocks have been completed.

Figure 7 shows the Designated Laser Areas for the three modes.

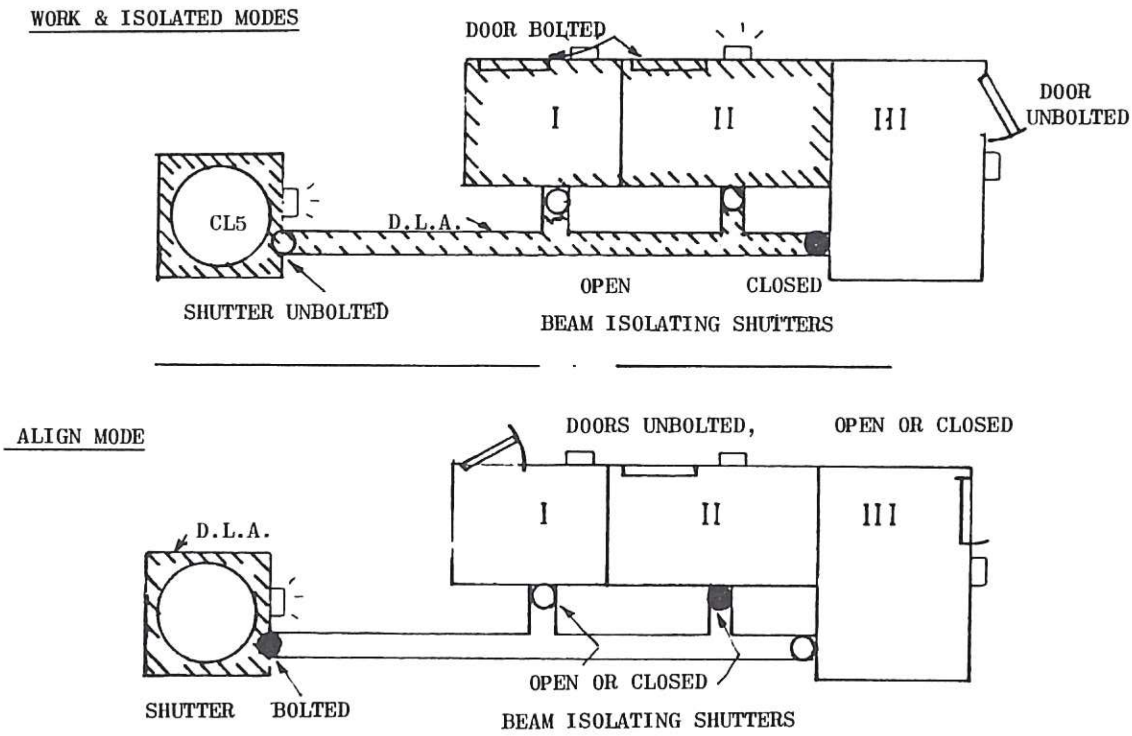


Fig.7 Designated laser areas in the three modes of operation.

3.2 The Beam Isolating Shutter

The beam isolating shutter (Figures 8 and 9) consists of a metallic restricting aperture in the optics box which can be sealed by a 16 mm thick copper dump block. The block has been shown to withstand 6kW for 10 minutes without deterioration. If the operation fails, it will do so in a safe state by virtue of the design. The dump block is held up, out of the aperture, by a small 24V dc electromagnet. Removal of the 24V. supply, by whatever means, automatically de-energises the magnet. The block falls under gravity, covering the aperture and preventing radiation leakage. The electromagnet is fixed to the actuator of a pneumatic cylinder which is driven up to open the shutter. A 'positive-break' type microswitch is fitted so that its contacts will close only if the block is completely down. This switch energises the workstation door-bolt solenoid.

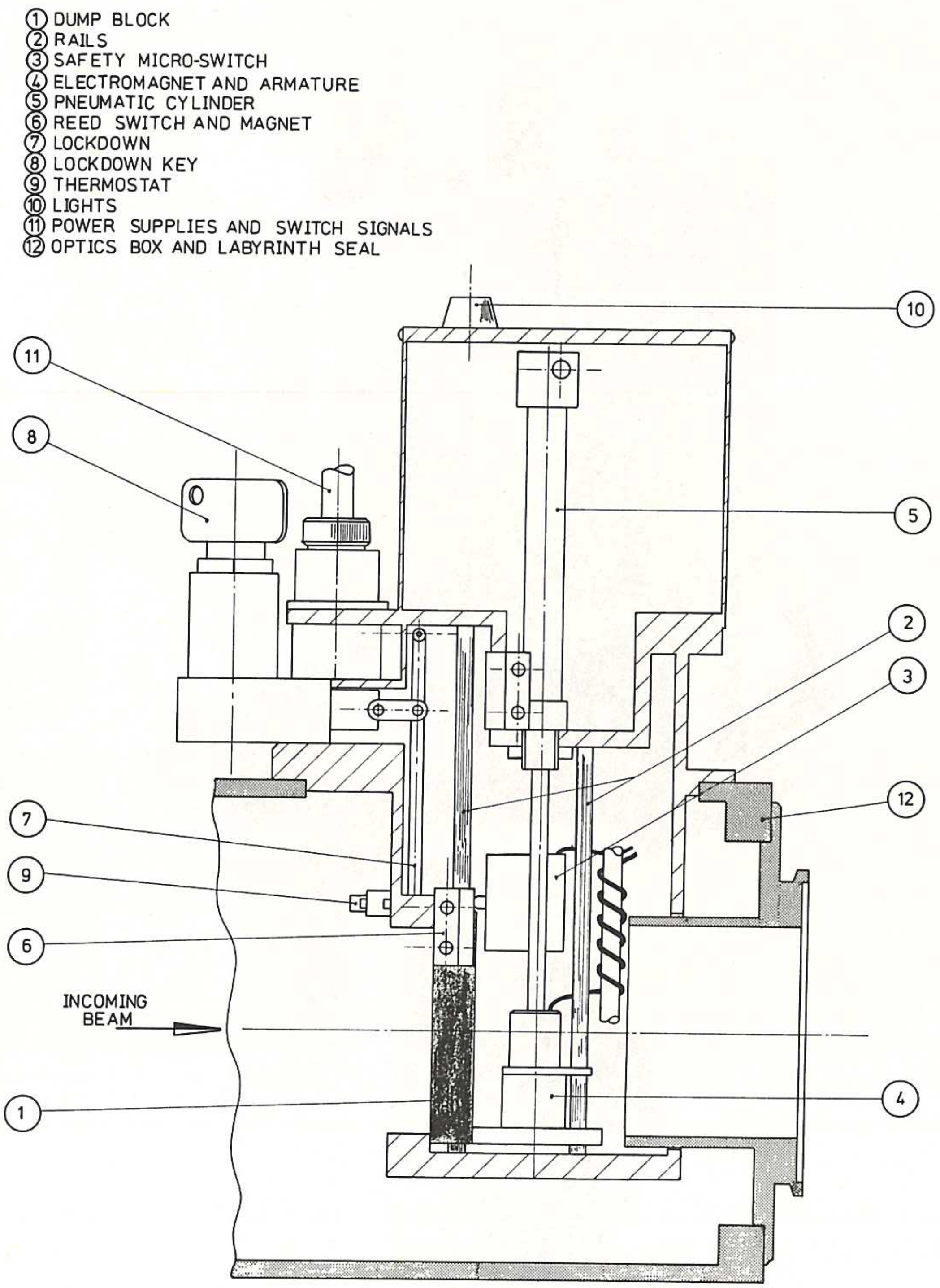


Fig.8 Schematic diagram of beam isolating shutter.

Local reed switches monitor the state of the isolating shutter for the PLC and the indicator lights, both on the isolating shutter and on the workstation local control panel. (A lamp colour coding(6) of green for closed, or safe, condition, and red for the open, or potentially hazardous condition, is used). A thermal switch is fitted to the front of the isolating shutter and is set to break at a temperature between 35°C and 60°C. This is also input to the PLC to prevent equipment damage.

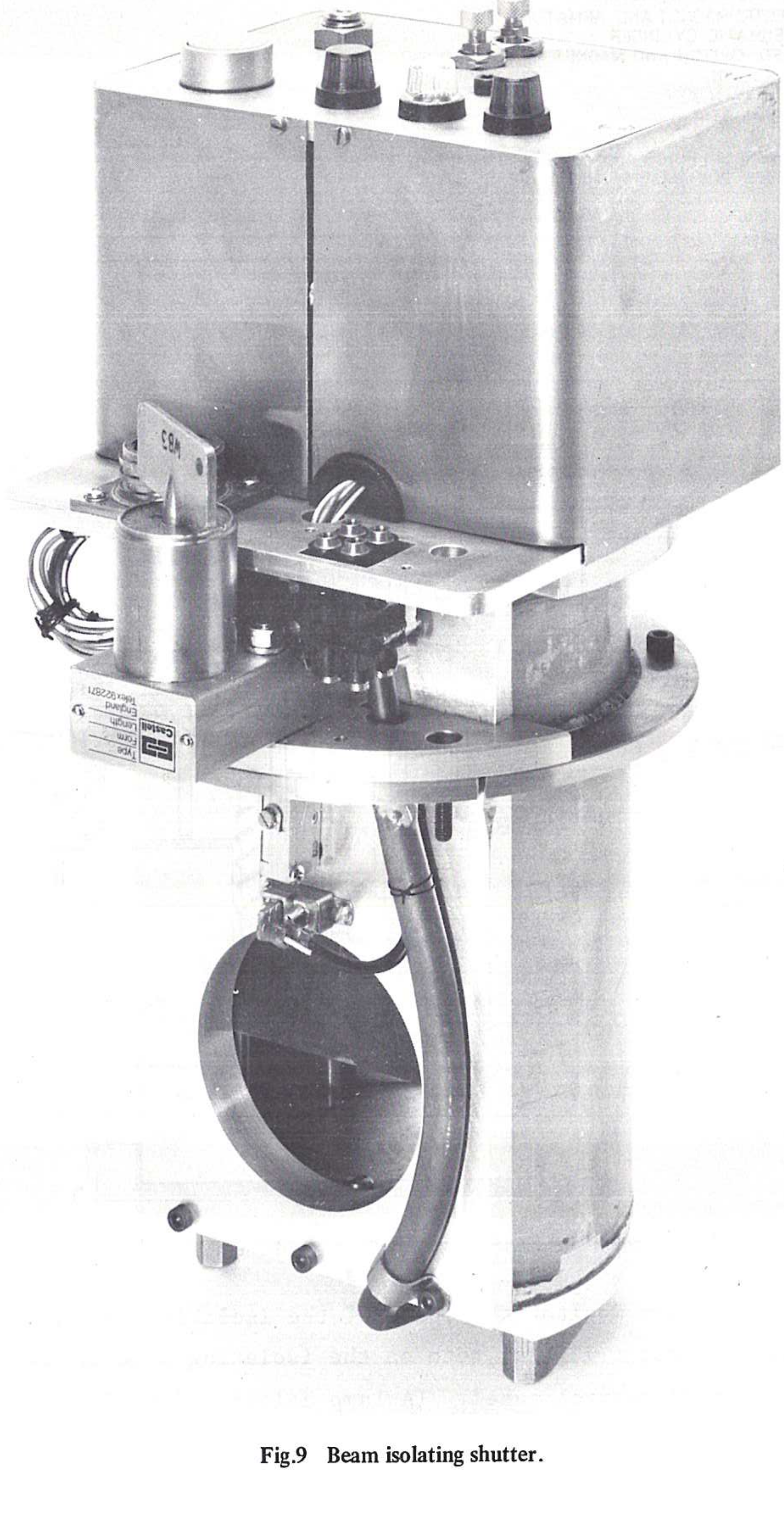


Fig.9 Beam isolating shutter.

The beam isolating shutter is fitted with a uniquely keyed lockdown device for use when non-involved personnel may be working in the workstation enclosure.

3.3 Laser Shutter

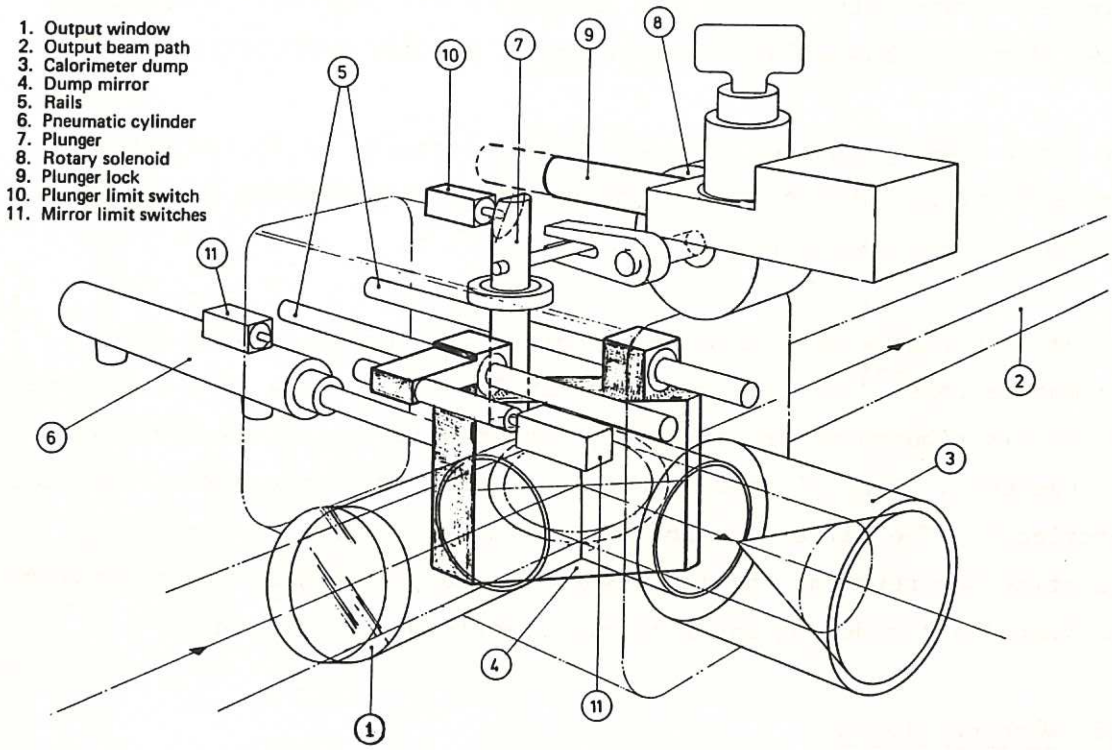


Fig.10 Schematic diagram of CL5 laser shutter.

The laser shutter consists of an 18mm thick water cooled copper mirror set at 45° to the beam; which, when closed, directs the output laser beam into a calorimeter dump and completely blocks the output port. The mirror is driven pneumatically on rails with a spring return to the closed position. The ends of the mirror stroke are monitored with limit switches. The dump mirror can be physically prevented from opening by a vertical plunger which falls by gravity, assisted by the spring return on its solenoid actuator. If the shutter key is removed the plunger is prevented mechanically from lifting and the mirror therefore cannot be opened. A limit switch on the plunger prevents the enclosure interlocks from being overridden if the plunger is not in the locking position.

The shutter is opened by means of solenoid valves controlled by the shutter button on the hand held control box.

3.4 Interlock Circuits

All interlock circuits are designed to break to a safe state thus inadvertent burning of the circuit or mechanical breaks present no hazard. Personnel access to workstation enclosures is interlocked to individual beam isolating shutters, whereas overall safety interlocks, (e.g. enclosure waterfilling and "emergency off" buttons) control the laser shutter (thus allowing common walls between workstations).

The 'beam ready' light on the hand held controller is an indication that all safety interlocks, PLC interlocks and processing procedure interlocks have been enabled.

Control interlocks with back up circuits, in compliance with HSE recommendations(7) and as prescribed in BS5304(4), have been used because of the distributed nature of safety features in the multiworkstation arrangements. Fig. 11 shows the circuit diagram of the hardwired safety interlocks. The direct mechanical locking facilities on the beam isolating shutters and the laser shutter are provided for safe working on the installation during major rearrangements and extensions.

3.5 Warning Lights

Large, twin bulbed, amber lamps are used for warning lights. The lamp on the laser head is illuminated if the laser is operating. If an isolating shutter is open, the warning light on the relevant workstation local control panel is illuminated. These lights therefore indicate the extent of the DLA at any time. Lights within the workstation flash whenever the beam is brought into that workstation and the laser head light flashes when the laser shutter is open.

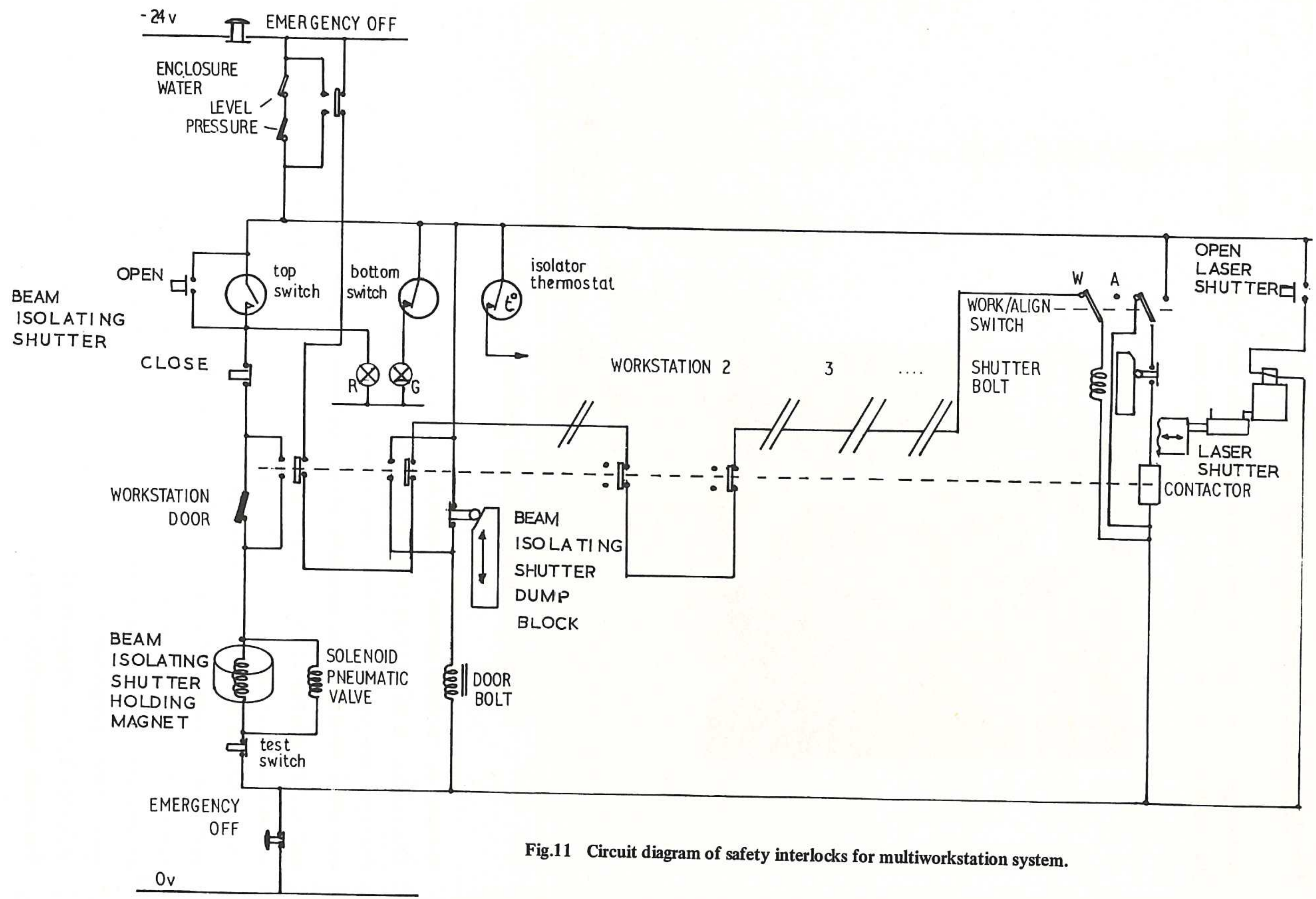


Fig.11 Circuit diagram of safety interlocks for multiworkstation system.

3.6 Laboratory Procedure and Quality Assurance

Early tests were made on dump block materials and Figure 12 demonstrates the need for testing of designs and modifications.

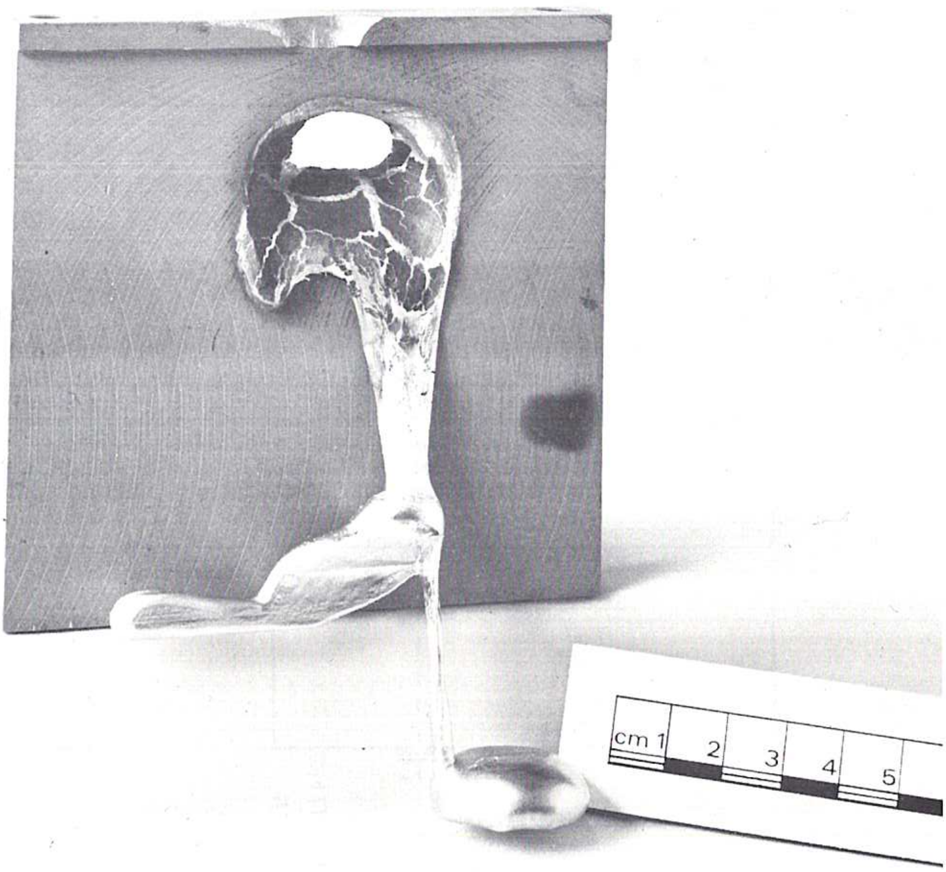


Fig.12 Effect of 5kW on 16mm aluminium block after 5 minutes.

Failure to operate correctly, although intrinsically safe, may cause interlocks to be over-ridden inappropriately. The beam isolating shutters are therefore cycled and safety checks are carried out before and after cycling. An assembly manual is provided for the construction and commissioning of any new shutter and shutters are checked initially, on installation, annually and at any instance of malfunction.

The system as devised and installed is safe provided that it is not modified or tampered with. Within the laboratory environment the Laser Responsible Officer is charged with the duty of ensuring this. Equipment within the safety system may have to be installed or modified as a development programme progresses. Safety components are inspected before installation or commissioning and during manufacture, if necessary, by an Equipment Responsible Officer. ERO's are charged with guaranteeing the safe completion of the work. Standing Orders are issued for the multikilowatt laser areas. They detail the duties and responsibilities of all involved personnel.

4. SAFETY ENCLOSURE MATERIALS AND SYSTEMS

As a result of an extensive research and development programme a suitable method for enclosing a workstation has been devised.

4.1 Protection and Detection Criteria

A list of criteria has been established for Laser Proof Materials. These materials must:

1) Withstand the full power of the unfocused laser beam indefinitely, or for a prescribed time (which is a function of the reaction time of the detection system) after onset of beam interception.

2) Provide early indication of beam interception if the beam is powerful enough to consume the barrier.

3) Diffusely re-radiate or absorb all received radiation.

In any safe enclosure there will need to be service supplies, fume extraction, ventilation and personnel access. All of these requirements imply that a safe enclosure will have discontinuities which must be rendered inpenetrable by stray radiation. A labyrinth system is used such that a beam cannot escape without at least two 90^{o} reflections. Reflecting (even diffusely reflecting) internal surfaces are therefore precluded. Discontinuities should neither be sited in the direct line of the primary beam route nor in the potential route resulting from displacement or omission of optical elements in the beam.

Criteria for a Laser-Proof System are that it must:

1) be constructed from laser proof materials,

2) have all discontinuities labyrinthed correctly,

3) not distort under laser irradiation to such an extent that its integrity is jeopardised,

4) be robust enough to tolerate the expected normal working conditions.

4.2 Modular Framework

A system of workstation enclosures which is sufficiently versatile for an R & D environment is constructed of frames (1m wide x ~ 2m high) made with hollow section anodized aluminium extrusion (42mm x 79mm x 2mm wall thickness). Two panels (.8m x 1m, up to 16mm thick) have to be fitted within the frame. Modules are joined together with a light-tight hinge strip (Figure 13). Doors are made of the same construction, fitting within the basic module frame with a labyrinth opening.

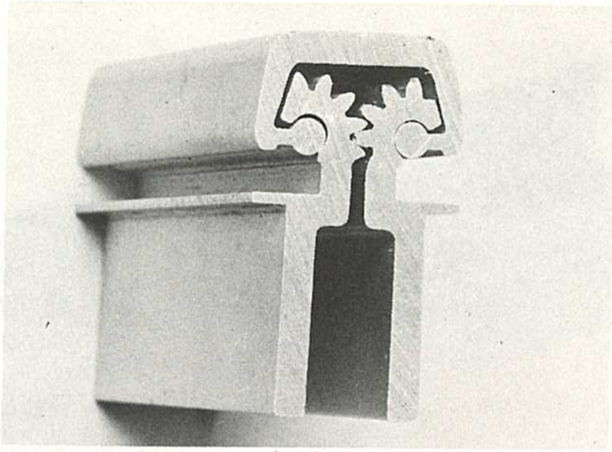


Fig.13 Light-tight aluminium hinge strip.

4.3 Laser Proofing

The burn through times of some typical materials are given in Table I. Transparent panels 16mm thick are inadequate to prevent beam penetration. As can be seen the aluminium box section also offers no intrinsic value as a laser-proof material. It can, however, be filled. Table II shows the results of tests on filling materials for the box section; they demonstrate the need for the following requirements:

1) Loose particulate material (easy and cheap filling).
2) Bond together on burning (preventing loss of filling).
3) High thermal conductivity (absorption and dissipation).
4) Does not melt, burn or evaporate away.
5) Indicates the beam presence.
6) Cheap.

Polycarbonate granules fit all requirements except No 6. Carbon granules fit all requirements except No 2.

G&S

A mixture of polycarbonate and carbon granules (G&S) fits all the above requirements. It decomposes to form a re-radiating carbon plug sufficiently far from the surface to prevent a 5kW beam burning through the section in 15 minutes. A cross section of a burnt specimen is shown in Figure 14.

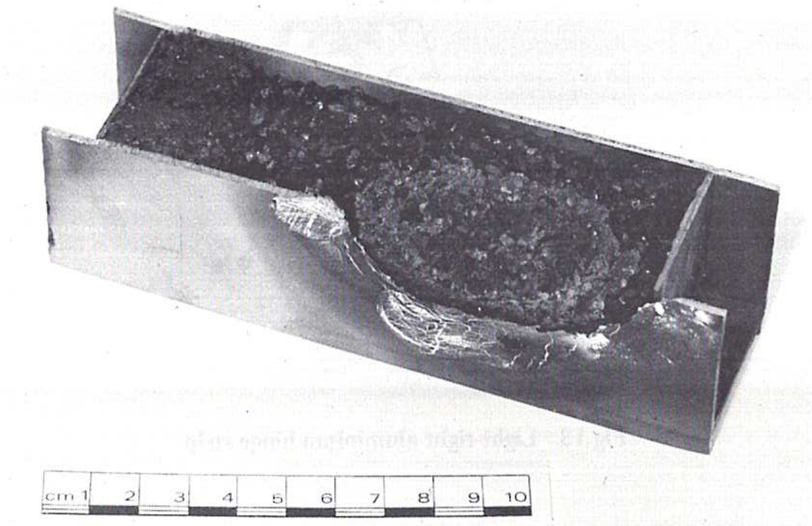


Fig.14 Cross-section of G&S filled frame after burning with 5kW for 15 minutes.

G&S can be dirty to use as a filling material. A consumable filling can be made using 'Vermiculite' and polycarbonate granules. The burn through times in this case are virtually proportional to the fraction of polycarbonate present (see Table II). Figure 15 shows a burnt specimen filled with this mixture.

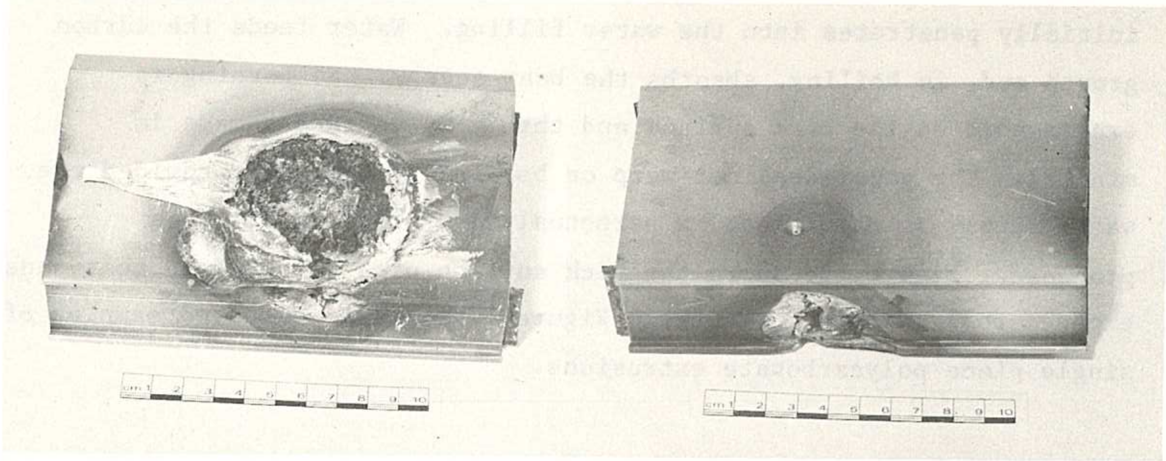
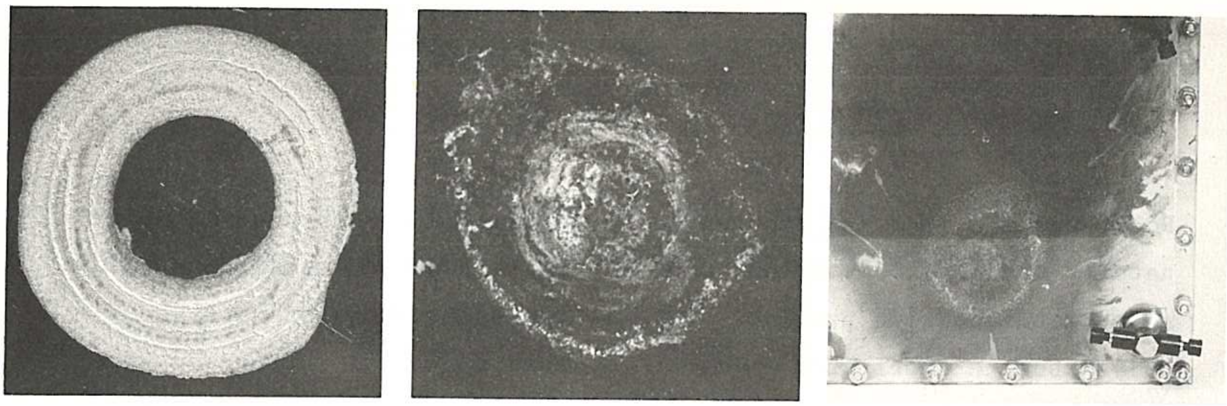


Fig.15 Sample filled with vermiculite and polycarbonate after exposure to 5kW for 11 minutes.

4.4 Laser-Proof Panels

The most readily available transparent panel material offering good protection is polycarbonate. When irradiated by a high intensity CO_2 laser beam, the surface first produces bubbles and then decomposes to produce a carbon foam growth which protrudes from the surface. (Figure 16 (a & b) shows a burn on polycarbonate compared with one on perspex.) This carbon growth absorbs the beam and reradiates the heat diffusely. Thick smoke is given off which is less toxic than that from burning wood. The bubbling experienced with low incident intensities or short duration exposures enables stray beams of lower powers to be detected.



a) Perspex 5kW, 2s

Waterfilled polycarbonate 7kW, 10 minutes

b) Front **c) Back**

Fig.16 Burns in perspex and polycarbonate.

Water Filling

To increase the"burn through" time indefinitely a sandwich arrangement is made with a water filled interspace(8). When burnt, a very small hole initially penetrates into the water filling. Water feeds the carbon growth and, in boiling, absorbs the beam energy. No burning is experienced on the back surface and the front surface damage is minimal. The panel does not warp or bow in any way and provided the water supply is maintained a perpetual laser-proof barrier is produced. Figure 16c shows the back surface of a waterfilled test panel exposed to 7 kW for 10 minutes. Figure 17 shows some tested samples of single piece polycarbonate extrusions.

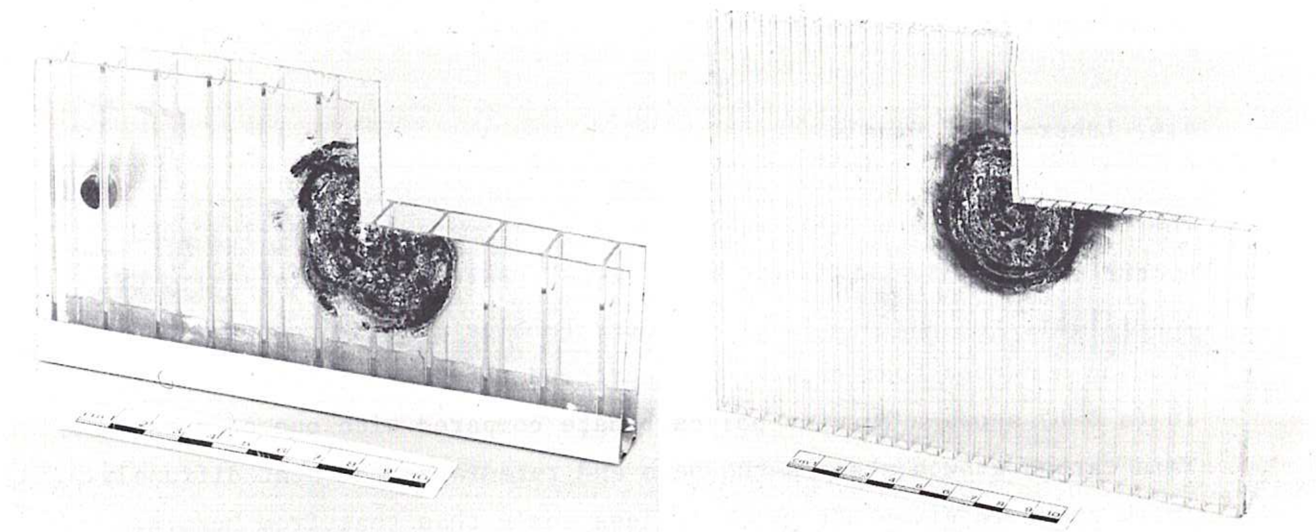


Fig.17 Polycarbonate extrusions used with water filling. Exposed to 5kW for 15 minutes.

Polycarbonate is tough and generally recognised for its unbreakable nature. Sealing polycarbonate panels against water leakage has been a major manufacturing problem. This is now undertaken for us by a polycarbonate fabricator. Figure 18 shows a typical fabricated water filled transparent window.

<u>Roof</u> panels are made of the reeded polycarbonate extrusion for lightness. They perform in the same way when "burnt" if the flow of water to the "burnt" area is ensured.

All panels are interconnected and fed from one water tank which is not continuously fed. The water level is interlocked with a tilting float switch. Roof panels are held above the vertical modules in an overlapping labyrinth arrangement.

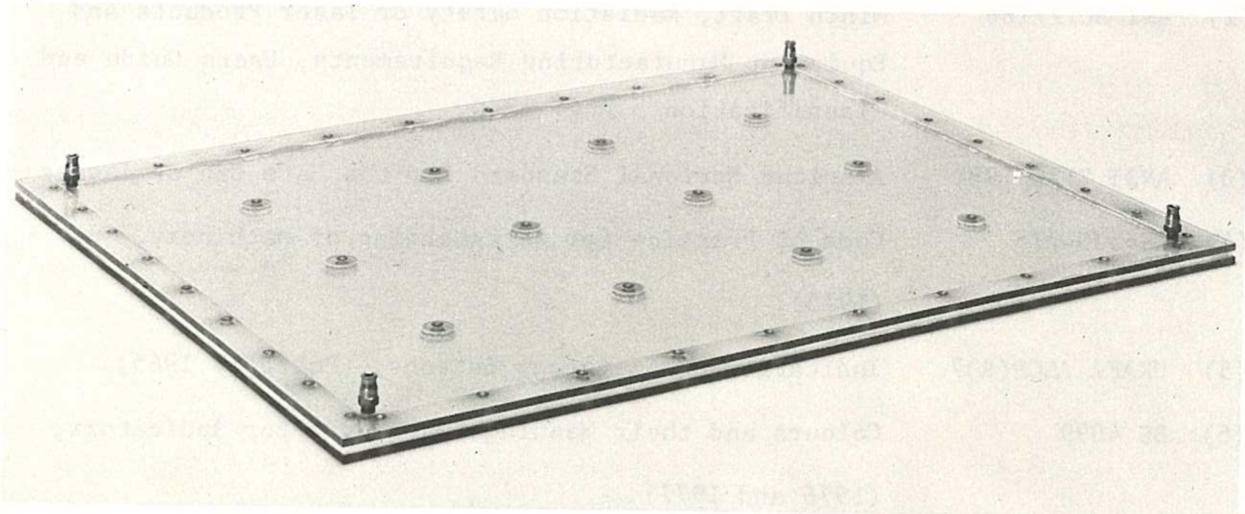


Fig.18 A fabricated water filled polycarbonate window.

5. Future Developments

The water filled polycarbonate laser proof panel system is being adapted to an overlapping form which can be used for cladding the insides of any form of (existing) enclosure structure. A self supporting roof system will be a requirement of this system.

Investigations are being undertaken into novel enclosure panel and beamline enclosure materials which will act in the shutter supply circuits. This will obviate the need for water and the associated problems.

Panel material development is at the state of producing a system where the material costs are no greater than for 2mm copper sheets and the chosen material is more laser-proof.

References

(1)	UKAEA RGSC17	Culham and Harwell Safety Code, Safety in the Use of Lasers in the Laboratory, (June 1974).
(2)	BSI 80/27186	Ninth Draft, Radiation Safety of Laser Products and Equipment Manufacturing Requirements, Users Guide and Classification 5 Aug. 1980.
(3)	ANSI Z136-1980	American National Standard for the Safe Use of Lasers.
(4)	BS 5304/75	Code of Practice for Safeguarding of Machinery, (1975).
(5)	UKAEA AECP(R)7	Indication of Emergency Buttons, (February 1965).
(6)	BS 4099	Colours and their Meanings when used for Indicators, (1976 and 1977).
(7)	HSW 24-B	Electrical Limit Switches and their Applications, (1974).
(8)	Patent Application No. P/25748/77	Safety Window for Lasers. B. A. Ward and N. C. Fenner, (20th June 1977).

TABLE I

Laser Proof Material Test Results - Burn Through Times of Basic Enclosure Materials (50mm dia. annular beam)

Material	Thickness mm	Laser Power kW	Burn Through Time	Signals	Comments
'Perspex'	6	5	7s	Thick black smoke	Fire risk, supports combustion.
Polycarbonate "Lexan"	6 12	5 5.2	20s 45s	Bright orange flame, black smoke. Bubbles Carbon growth	Does not support combustion. - low incident intensity - high incident intensity
Mild Steel	3	5	25s	White flame	
Anodised Aluminium	2 x 2mm 16	4.5 5	7s 5 min	None	$(100mm)^2$ *for good conductors the sample size is important.
Mortar	44	5	73s	Smoke	Also may crack.
Concrete (Banbury)	50	3	4 min	Smoke	Also may crack.
Copper	10 6 3 1.8	5 6.5 6.5 6.5	∞ ∞ (**32 sec) ∞ (30 sec) 2½ min (10 sec)		$(100mm)^2$ * **Infinite protection by virtue of reflectivity Burn-through times for samples with coated surfaces are shown in brackets.
Graphite	25	5	∞	None	
Carbon	25	5	∞	None	

TABLE II

Filling Materials for Hollow Aluminium Extrusion

Filling	Power kW	Burn Thro' Time	Test Time	
Nothing	4.5	7s	-	
Sand	4.3	1.3min	-	*
Polycarbonate sheet 6mm	5.0	1.5min	-	
Charcoal (15mm pieces)	4.2	3.8min	-	**
Charcoal (40mm pieces)	4.0	4.5min	-	**
Vermiculite and Polycarbonate 8:2	4.4	7.7min	-	
Vermiculite and polycarbonate 7:3	5.0	11.0min	-	
Graphite Rods 1" dia	4.0	-	5min	
Polycarbonate granules	4.2	-	10min	
G&S mixture 1:3	5.0	-	15min	

*Sand falls out (but test with 50mm of sand between 3mm steel no burn through).

**Granule size crucial - small falls out, large leaves voids.