ROBOT SAFETY

Department of Labour

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ABSTRACT

This booklet describes the hazards associated with application of industrial robots and the basic principles of guarding to comply with the Machinery Act 1950. Typical hazards are impact and trapping by the mechanism, and movement of robot arm or dropping workpieces. Malfunction and human error may also lead to unexpected movement of the robot arm, which can crush and cause injury to persons around. Other hazards are electrical shock, burns, radiation, fume, etc. The robot work envelope can be guarded by fixed barriers with interlocked gates for access and incorporating parts transfer by shuttle mechanism or rotary positioner. Trip and presence sensing devices can also be used to guard the work envelope of robot by means of photoelectric light beams or pressure sensitive mats which both must be a fail to safety type. At close proximity to robot, trip devices may be fitted on the robot arm itself for stopping the robot movement when tripped.

INTRODUCTION

An industrial robot can be defined as a position controlled, reprogrammable, multifunctional manipulator having a number of degrees of freedom in three-dimensional space and capable of handling materials, parts, tools, or specialised devices through variable programmed motions for the performance of a variety of tasks.

Due to the characteristic of the industrial robot, it can present two opposing viewpoints in terms of industrial safety. The application of industrial robots permits the removal of the need for humans to perform certain dangerous and harmful operations, hence increasing safety. Applications in areas like welding, forging, sandblasting, painting, etc., enable workers to be free from adverse and unsafe working conditions.

However, on the other hand, the industrial robots themselves can also create dangerous conditions and threaten human safety. Accidents and even fatalities as reported from overseas have proven that industrial robots can be hazardous if no safeguard is provided to eliminate the potential hazards.

Therefore, it is essential that robot users and manufacturers recognize the potential hazards and implement safeguards to eliminate the hazards. This booklet describes hazards associated with the application of industrial robots and the basic principles of guarding to ensure human safety. Hazard analysis and the safety precautions and procedures to be taken for programming and maintenance of the robot are also discussed.

HAZARDS ASSOCIATED WITH ROBOTS

The main hazard associated with the application of industrial robot is the working envelope of the robot. The ability of the robot to move in free space which cover a wide area, change configuration and produce unexpected motion immediately can cause hazards to persons operating or standing in the vicinity of the robot. Therefore in any robot installation, hazard analysis should be carried out to identify hazards so that safeguards can be implemented to prevent the occurrence of accidents.

Malfunction and human error can lead to the unexpected movement of the industrial robot which include:

(a) Aberrant behaviour of robots caused by control system faults.

(b) Jamming of servo-valves.

(c) Robot movement cutting its umbilical cord.

(d) Splitting of unions on exposed hydraulic hoses.

(e) Fault in data transmission causing a larger than anticipated movement of the robot arm.

(f) Faults of welding gun and tooling parts.

(g) Programming and other operational errors.

(h) Precision deficiency, deterioration.

(i) Incompatibility of jigs and other tools.

There are basically three potential hazards associated with robotic systems which are as follows:

(a) Impact — this involves such things as being struck by a moving part of the robot, or by parts or tool carried or manipulated by the robot. It can be caused by the unexpected movement of the robot or by the robot ejecting or dropping workpieces or molten metal.

(b) Trapping — this can be caused by the movement of the robot in close proximity to fixed objects like machines, equipment, fences, etc. Trapping points can also be caused by the movement of the work carriages, pallets, shuttles or other transfer mechanisms. They can also be presented on the robot itself on the arm or mechanism of the robot.

(c) Other — this would include hazards inherent to the application itself like electric shock, arc flash, burns, fume, radiation, toxic substances, noise, etc.

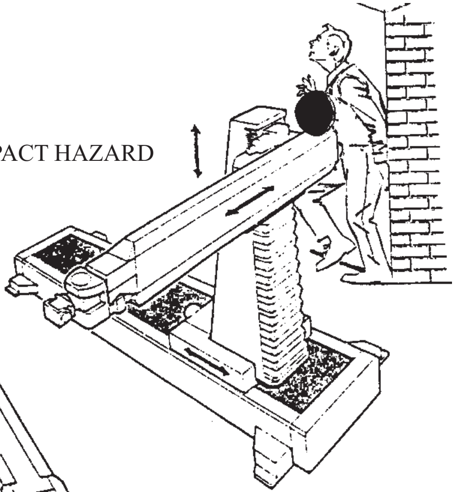
These hazards can arise from several sources and should be considered in a typical robot installation which include:

1. Control Errors

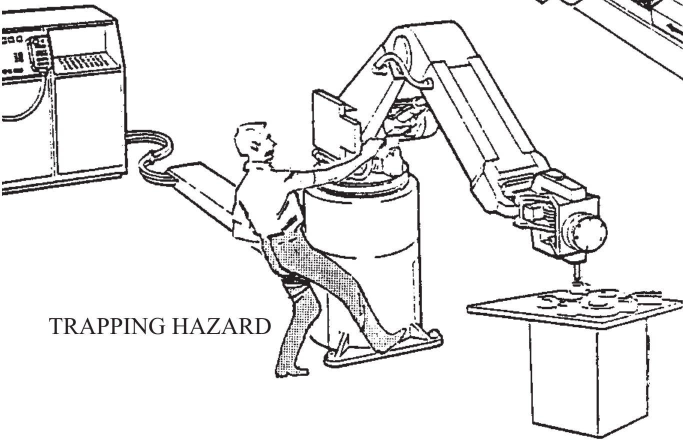
These are faults within the control system of the robot like software errors, electrical interference, or faults in the hydraulic, pneumatic, or electrical sub-controls associated with the robot. Electrical interference can come from two sources — line noise and radiated frequency interference. Both types are hazards because they can cause erratic operation of microprocessor controlled robots.

2. Mechanical Hazards

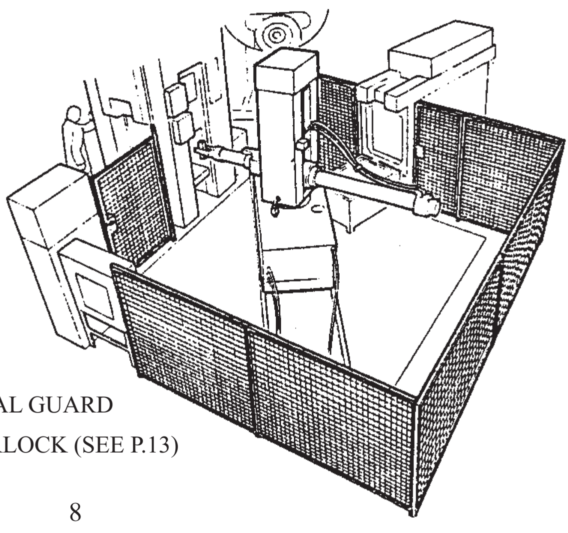
These can be caused by parts or tools carried or manipulated by the robot like sharp edges, heavy weights and exposed electrodes. Mechanical failure may lead to the ejection of workpieces by the robot gripper. Causes of this hazard can be due to overloading, corrosion, fatigue and lack of maintenance.



IMPACT HAZARD



TRAPPING HAZARD



MECHANICAL GUARD
WITH INTERLOCK (SEE P.13)

3. Environmental Hazards

Application of robots can also cause an environmental hazard in some cases. Examples of this are welding robots which usually produce large amounts of fumes, arc flash and flying particles. Other environmental hazards may include dust, vapour, x-ray, laser, ultraviolet, ionising and non-ionising radiation, flammable and explosive atmospheres.

4. Human Errors

In most robot installations, persons may have to work close to a robot or enter the guarded area of a robot and hence exposed to trapping points and impact. This occurs during programming, teaching, maintenance, or in work handling close to robot or at the loading/unloading station. Lack of familiarity with the equipment is a major cause of human error which can be hazardous.

5. Ancillary Equipment

In most robot installations, the robot usually works in conjunction with other equipment like conveyor, machine tool, press, shear, etc. This equipment can also create a hazard if the dangerous parts are within reach of a person and not enclosed by guards.

FAULT TREE ANALYSIS

Overseas reports indicated that most of the accidents related to industrial robot were due to the unexpected movements of robots, whereby the operator entered the working envelope when the robot had stopped working (or was working very slowly) and the robot suddenly and unexpectedly started moving (or accelerated).

Each of the accidents occurred because the robot started to operate without the victim's knowledge, who had entered the danger area with little concern since the robot was idle. Therefore even at slow operating speed, robot arms can crush a person as they move from outside the worker's line of sight, catching the unaware victim from behind.

A fault tree analysis of the hazard due to the element of the unexpected robot movement is shown in figure I. The potential dangers in the working environment are the result of combination of unsafe conditions and unsafe actions. Fault-tree analysis is a technique that can be used to study the chronological progression of causes and effects that have contributed to a particular event. It is a logical approach to identify the areas in a system that are most critical to safe operation.

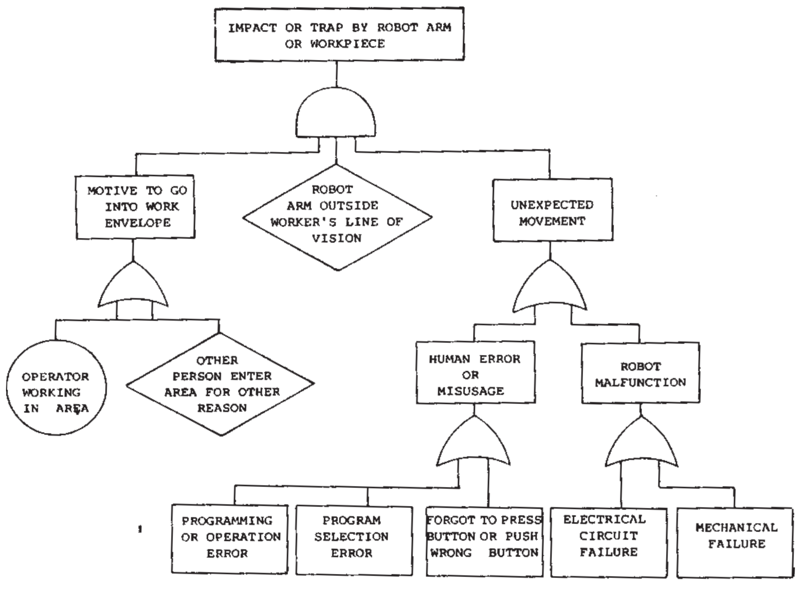


FIG 1: FAULT TREE ANALYSIS OF HAZARDS ASSOCIATED WITH ROBOT

RISK ASSESSMENT

Recognizing and identifying potential hazards in operation of a robot is essential. Therefore the first thing to do with a robot installation is to carry out a hazard analysis and study the layout to determine whether or not the robot is capable of causing injury. If there is a foreseeable risk of injury from operation of the robot due to its power and size, then guarding should be provided. The method of guarding and the need for interlocking is based on the degree of risk. Each installation is to be considered individually taking into account the various ways of operation, e.g. programming/teaching, normal operation, maintenance, and each mode is examined for designed and aberrant behaviour.

The factors determining the risk are:

1. The frequency of access to the danger area., etc
2. The foreseeable risk and severity of injury in the event of interlock failure, considering:
   (a) the working method;
   (b) the necessity of access;
   (c) the action of the part guarded by any type of interlock;
   (d) the characteristics of the robot.

Usually it will be a matter of judgement based upon experience and with the assistance of whatever resources available to establish the risk presented by the robot and its associated equipment.

REQUIREMENTS OF THE MACHINERY ACT 1950

Sections 15, 16 and 17 of the Machinery Act 1950 require that moving parts of any prime movers, every part of transmission machinery, and every dangerous part of any machinery to be securely fenced, unless the parts are in such a position or of such construction as to be as safe to every person employed or working on the premises as they would be if securely fenced.

With some conventional machines the concept of dangerous part is usually identified as located inside the machine. By contrast, one characteristic of the robot is that a large surrounding area can be potentially dangerous. In the case of danger space overlapping the working zone of human operators, conventional machines are always under the control of humans, and the causes of accident are always identified as due to operator errors or to erroneous handling of the work to be done by the machine. However, with industrial robots, the danger space is anywhere within the range of robot arm's reach. Furthermore, the danger area would extend over a wider area should the robot lose control of the workpiece and ejects it. Therefore the maximum range of hazard space is not immediately recognisable, and hence precaution should be taken to safeguard this area.

GUARDING DURING OPERATION

Generally, it is possible to identify the hazard areas associated with robots in terms of three levels

Level 1 is the work station perimeter

Level 2 is within the work station

Level 3 is adjacent to the robot arm.

Different requirements of guardings may be applied for each of these zones.

Level 1, the perimeter, can be guarded by a physical barrier, usually a combination of fences, gates and perhaps presence sensing devices.

Level 2 involves the sensing of the presence of humans anywhere within the free space in which the robot moves by means of presence sensing devices. In comparison to perimeter guarding, the emphasis is on detection rather than on a physical barrier.

Level 3 requires the capability to detect the presence of a person or other obstruction in direct contact with, or in immediate proximity to the robot arm, and to stop the robot movement immediately. This is done by using trip device or collision detector strip working on a similar principle as the safety mat.

At least one level of guarding will be required for most robot installations. Depending on the application, set up and risk assessment, it may be necessary to use more than one level of guarding in some cases.

Mechanical Guards with Safety Interlock

The basic principle of guarding the work station perimeter, which can be applied to most installation, is to install fixed fencing or permanent barriers to enclose the working area of robot with interlocked gates for access so that people are prevented from entering the area while the robot is working. The barriers should be high enough to prevent a worker climbing over it without considerable effort (at least 1.5 metres high) and fitted with sheet material or mesh to prevent reach or access. The advantage of a fence-type barrier is that it is capable of stopping a workpiece which might be ejected by the robot's gripper while in motion. The robot's reach envelope diagram should be used in planning the barriers so that adequate clearances are maintained between robot arm and barriers.

The barrier can also act as a screen to protect persons in vicinity of the robot from spark and arc flash produced by welding robot.

Access gates should be of similar height and construction, and be interlocked with the robot control by normally closed limit switches and incompliance with the principles outlined in the Department's booklet *Electrical Interlocking of Machinery Guards*. It is important that the interlocking system should operate on all access gates. Once the gate has been opened, the robot and associated machinery should not be able to operate in automatic cycle until the gate is closed, and the machine control reset. Closing the gate alone should not initiate a cycle start. A manual restart switch should be used to power the robot up again.

Figure 2 shows the layout of the physical barrier enclosing the perimeter of robot working area with interlocked access gate. The barrier should be located with sufficient clearance outside the farthest extremes of robot's reach with its tooling. Although the robot may not be programmed to go beyond certain point in its work envelope, in the event of a failure, all work envelope points are accessible by the robot. The work envelope of the robot can also be restricted by fitting mechanical stops on the robot axes, either internally in the actuators or externally on the linkages or joints.

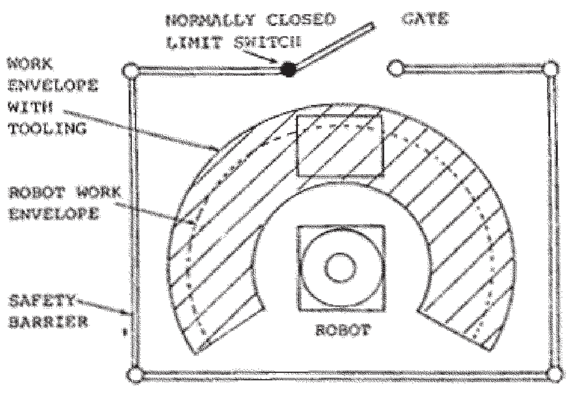


FIG 2: BARRIER WITH INTERLOCKED ACCESS GATE

Figure 3 show another method of ensuring safety where operator has to present and remove parts from the robot. The operator can stand outside of the robot work envelope and parts can be transferred by a shuttle mechanism into the robot for operation. By working at two alternate stations, the robot can be fully utilized effectively and safely together with the operator.

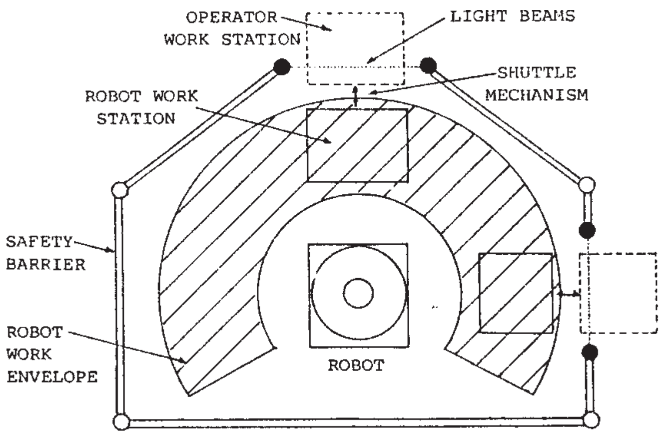


FIG 3: BARRIERS WITH SHUTTLE MECHANISM

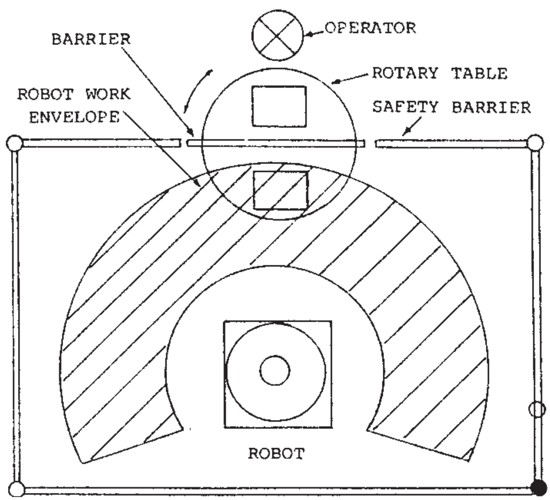


FIG 4: BARRIERS WITH ROTARY TABLE

Figure 4 show a different shuttle system. A two-position rotary table or positioner is used so that the operator is on the other side while the robot is working on one side with a physical barrier between the two stations. This system enables the operator to load and unload the workpiece while the robot is doing the work on the other side. The force required to rotate the table should be minimised to prevent any possibility of injury during contact by the operator or if trapped.

Robot installations which cannot stop immediately, due to cycle of operation and have a run-down time, must have a time delay mechanism fitted to the gate interlock to prevent access to the moving, dangerous parts of the robot like the use of a trapped key interlock (key exchange) system. It works on the principle that the master key, which controls the power supply to the robot through a switch at the master key box, has to be turned off before the key for the guard door can be released for opening the lock. A time delay or motion sensing unit can be incorporated into the system.

A device which will prevent personnel entering the enclosed operating area of the robot until all the hazards have been eliminated can also be used. The safety system has a three-position switch control and is installed on the guard door frame.

In position one, the guard is locked closed and the robot operated automatically. By turning the control to the second switch position, the robot is instructed to stop at the next safe point in its operating cycle. Only when this has been achieved can the operator turn the control switch to the third position to gain access to the area around the robot. Normal operation of the robot cannot resume until the guard is safely closed and locked.

The disadvantage of mechanical guard is that it does not give any protection for people working inside the fence during programming, adjustment, maintenance and service. The physical guards themselves can cause a trapping hazard between the robot arm and the barrier if they are placed too close to the robot. Operators should be able to move outside the robot's working envelope if something happens. In cases where the robot working cycle is very short and the operator has to enter the work envelope every frequently, then an interlocked gate may not be very convenient.

Presence Sensing Devices

If an interlocked gate for access at load/unload station is not suitable, another alternative in guarding is to use presence sensing devices such as photoelectric light beams or pressure-sensitive mats. The advantage of these devices is that it is easier to gain access to the robot. When a presence sensing device is tripped, a separate actuation of the controls must be required to reactivate the robot working cycle.

In Level 2 guarding within the work station perimeter where the operator has to enter the work envelope to carry out work frequently, the presence sensing device should be arranged to operate in the horizontal plane and cover a ground area. This can be done by horizontal light beams guards set around waist level which will be less prone to accidental damage. A low set of horizontal system has to detect narrow ankles rather than bulky waistlines and hence requires closer-set beams.

The alternative to light curtains is to use a pressure-sensitive, mats which is usually referred as a "Safety Mat". These can be placed on the floor around the robot and when stepped on, turn the robot controller off or prevent the robot from cycle starting. A safety mat is a convenient way of guarding at the load/unload station and the only disadvantage is their susceptibility to damage depending on the condition of application.

The photoelectric light beams guard and pressure sensitive mat must be of a fail to safety type. That is the control system as a whole, including machine safety system, is designed so that in the event of single component failure the overall safeguarding system will not fail to danger. Guidelines given in the Health and Safety Executive Guidance Note PM 41 and the BS 6491 should be followed for the installation and maintenance procedures of photoelectric light beam system.

In general, presence sensing devices should only be used as a secondary forms of guarding or where limited access is required like at the load/unload stations. They can also be placed within the work station perimeter guarding in a high-risk installation to act as a back-up in the event of a failure in the interlock access gate.

Trip Devices

Trip bars and collision detector strip which works on a similar principle as that of the safety mat may be mounted on the robot arm itself for Level 3 guarding of smaller robots where operator has to stand at close proximity to the robot when it is idle. When depressed by contact with an obstruction, an impulse from the detector will cause, via a suitable interface, an emergency stop of the robot. Similarly, the collision detection device must be also a fail to safety type. The detector should be sufficiently sensitive to permit the robot arm movement to stop immediately.

Emergency Stop Switches

Emergency stop button and/or trip wires should be installed around the perimeter of the robot's operating area in easily accessible locations as well as on the robot's teach box and control console. Hitting the emergency button stops power to motors and causes the brakes on each joint to be applied immediately.

All safety devices and stop buttons should be hard-wired to the robot controller and power brake system using hardware-based components and not part of the software or robot control programme, so that the robot can be stopped as quickly as possible.

Screens between Station

If a robot installation has a number of workstations within the work envelope, and the operator is required to enter a work station while the robot is working at the other station, a hinged screen fitted with normally closed limit switch can be installed between each station to safeguard the operator. In the event of a malfunction or run away situation, the robot will hit the screen which will activate the switch and stop the robot movement immediately. The swinging movement of the screen should be limited by stop so that it will not hit the operator. The final stop for the screen movement should be capable of stopping the robot under full speed run away condition. Figure shows a typical arrangement.

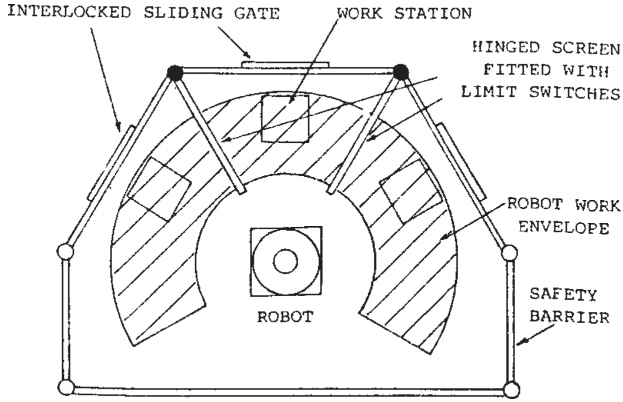


FIG 5: ROBOT WITH SEVERAL WORK STATIONS

Work Envelope Limit Stop

When space is limited, it is tempting to rely on the controller and programming to restrict the travel of the robot to the operating range. This is not safe practice to limit robot travel. Controller malfunction and bad programming may lead to the robot performing hazardous movements. Physical stops should be used to restrict movement of the robot within its operating envelope. These stops should be capable of stopping the robot under full speed run-away conditions. Every robot, regardless of the power system or type of controller, is capable of run away conditions upon failure of certain component and hence must be guarded against at all times.

PROGRAMMING OR "TEACHING"

Programming of industrial robots is generally achieved by "leading" the robot through the motions it is required to perform, by operating controls which cause the motions. Alternatively, a light "imitation" robot arm may be physically forced to perform the operation required, with the relative motions transmitted to the controller, so it can cause the main robot arm to reproduce the motions. In either case, the operator is required to stand relatively close to the robot arm, often within the operating area. As this is standard practice the Department cannot take exception to it, but certain precautions must be observed.

(1) The operator must be thoroughly trained and aware of the dangers and precautions to be taken;

(2) The robot should be prevented from moving at high speed during the teaching operation;

(3) The operator must have immediate and easy access to an emergency stop button;

(4) The operator should stand where there is minimum possibility of being trapped between the robot arm and any fixed object, allowing for the need to observe the operation clearly, and stay out of areas where they might be hurt in the event of a robot malfunction;

(5) It is strongly recommended that an observer be present, standing outside the operating area and with immediate access to an emergency stop control;

(6) Where necessary, protective clothing or equipment should be used e.g. bump hat or protective helmet if there is a risk of head injuries;

(7) The teach box must be designed so that the robot can move as long as a switch is pressed by the operator's finger. Removing the finger must cease all the robot's motions.

MAINTENANCE

There must be provision for effectively isolating the robot arm and any other machinery within the operating area from its power source for maintenance purposes. The use of a hold card or lock system on this isolater is recommended. If, at any time, access to the robot arm (or other equipment within the operating area) is required for maintenance while power can be applied to the arm, precautions as mentioned before must be observed.

ANCILLARY EQUIPMENT

Very often, a robot installation includes equipment such as conveyors or machine tools. In general, these should be included in the fenced area and isolated whenever access is possible. Where practical, this equipment should be isolated during teaching operations. Power-operated jigs, clamps and moveable welding tables should be operated with the minimum force necessary, and if this force is so low that trapping will not result in injury, then no guarding will be necessary, even if this equipment can be operated under power while the operator has access to it.

ASSOCIATED SAFETY AND HEALTH MATTERS

(1) Robots have a high work capacity and, for example, welding robots working in full production will produce large amounts of fumes plus other hazards such as arc flash and flying particles. As such, care is required when siting robots to ensure that workers in the vicinity of the robot work site are not subject to these hazards and that ventilation systems are expanded to cope with the additional fume is generated.

The environment around a robot should also be protected from hazards peculiar to a particular installation such as:

(i) Ultraviolet rays from arc welding;

(ii) High-intensity light from laser beams;

(iii) Sparks from spot welding;

(iv) Vapours from paint spraying.

(2) Where robots are used for materials handling, there may be a risk of workpieces being ejected (thrown) if the robot malfunctions. Where such a risk exists, the protective barrier should be of sufficient construction and height to prevent injuries to staff in the vicinity.

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