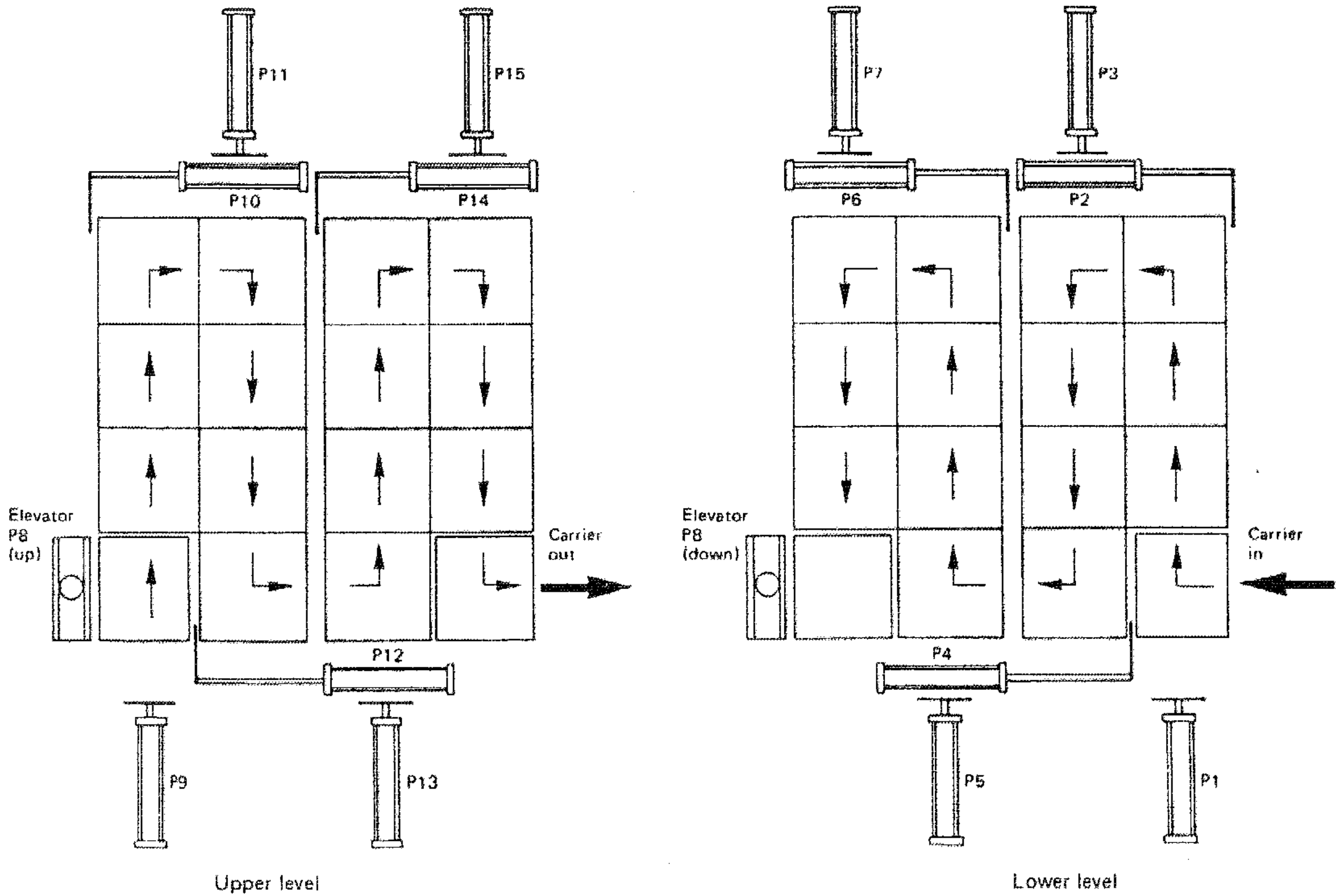

FIG. 7. Plan of the two levels of the transport mechanism of the JS6300 irradiator. (By courtesy of Nordion International Inc.)

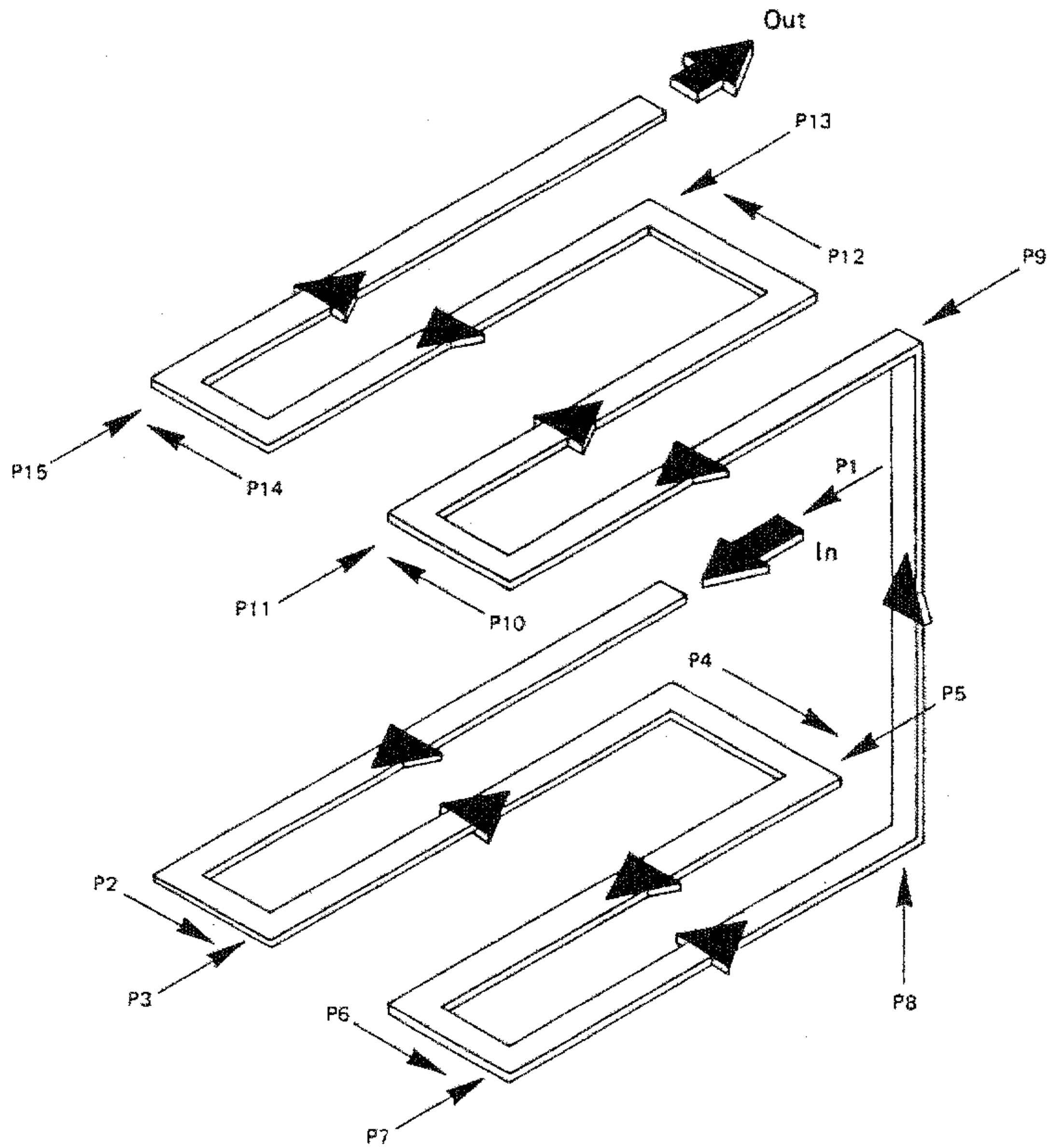

FIG. 8. Schematic diagram of the transport of product boxes in the irradiator. (By courtesy of Nordion International Inc.)

a sequential movement of the pistons is initiated. This advances each product box by one position and shifts one completely processed product box to the upper shelf of a product carrier which transports it from the irradiator.

Between 1975 and 1981, a number of incidents occurred at irradiators from the same supplier, in the USA and elsewhere (including the incident in San Salvador in 1975) in which damaged product boxes obstructed the source rack and caused it to jam. Consequently, in 1981, the supplier distributed *Warning Notice IND-81-1*, in which it recommended that a steel source shroud be fitted around the irradiation position. It was also recommended that the condition of the boxes be routinely checked and that boxes in marginal condition be replaced.

The owner of the plant received this warning notice but never had its recommendations implemented owing to their cost and the increase in the exposure time that would be necessary to compensate for the shielding effect of the shroud. By the time of the accident in February 1989, the product boxes had been in use for a number of years. Many were in extremely poor condition and had been repaired with adhesive tape.

3.5. SAFETY INTERLOCKS AND ACCESS CONTROL

The following is a description of how the intact system as installed was intended to function.

3.5.1. The control panel

The wall mounted control panel (Fig. 9) has power and machine key switches and display lights for machine ready, machine on, source up and source down. A master timer, an overdose timer (which shuts down the irradiator in the event of a malfunction of the master timer) and a cycle counter are also mounted on the control panel.

Although Fig. 9 shows the panel as having illuminated legends, at the time of the accident the panel had no markings to indicate the significance of the controls or the warning lights. (However, the workers interviewed who were responsible for operating the controls were familiar with their functions.) In addition, a skylight above made it difficult to see whether the warning lights were on in the daytime.

3.5.2. Radiation monitoring

An L118 radiation monitor is interlocked with the personnel access door to prevent access to the radiation room if there are abnormal radiation levels inside when the source should be in the storage position. The L118 radiation monitor (see Fig. 10) is mounted on the wall in the radiation room and detects background radiation with a high sensitivity by means of an array of nine Geiger-Müller tubes. The monitor is designed to give an alarm condition for exposure rates in the range from the equivalent of about eight times that due to natural background radiation to greater than 10 000 $Sv \cdot h^{-1}$ (10^6 $rem \cdot h^{-1}$). Figure 11 is a schematic representation

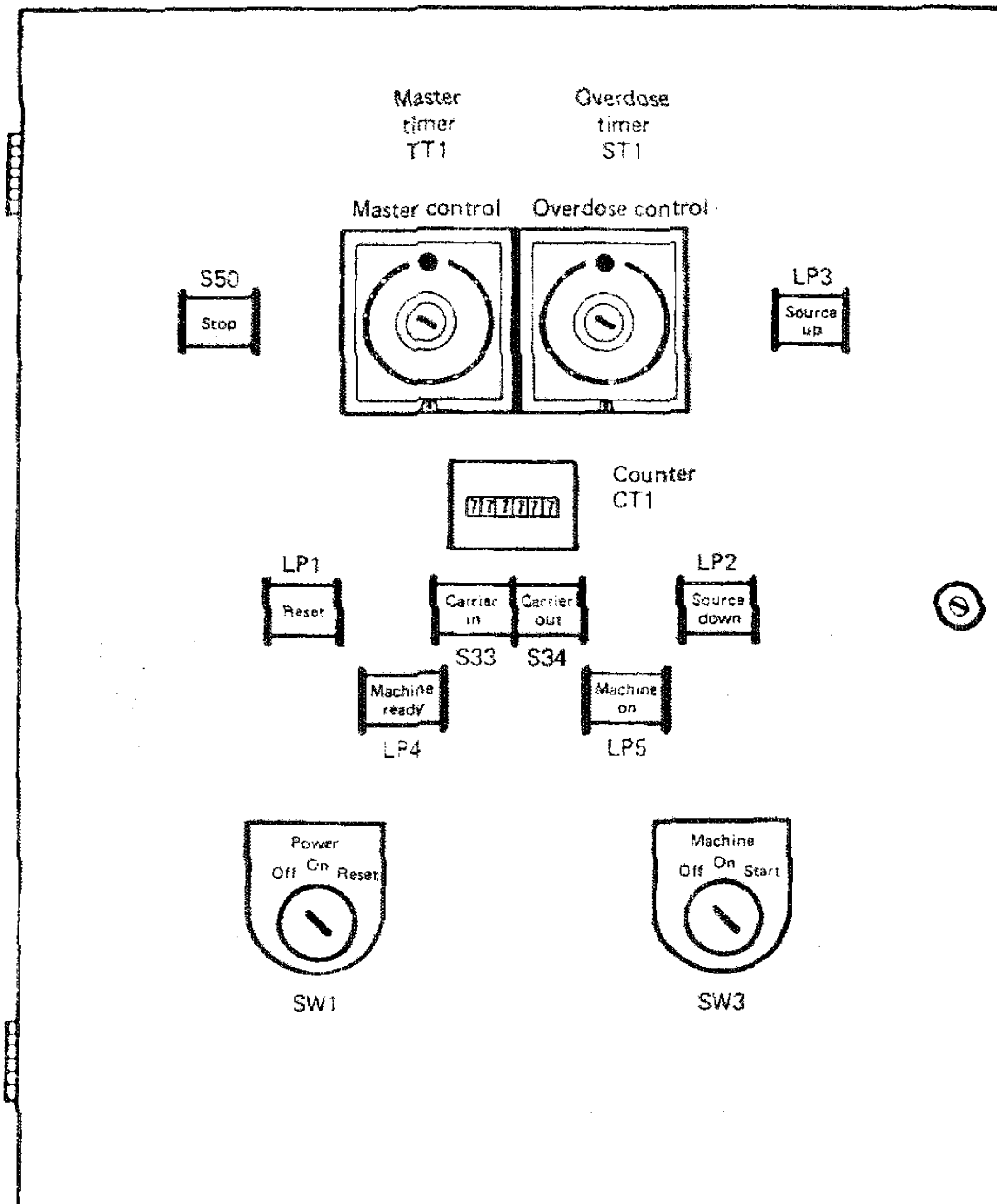

FIG. 9. The control panel of the JS6300 irradiator. (By courtesy of Nordion International Inc.)

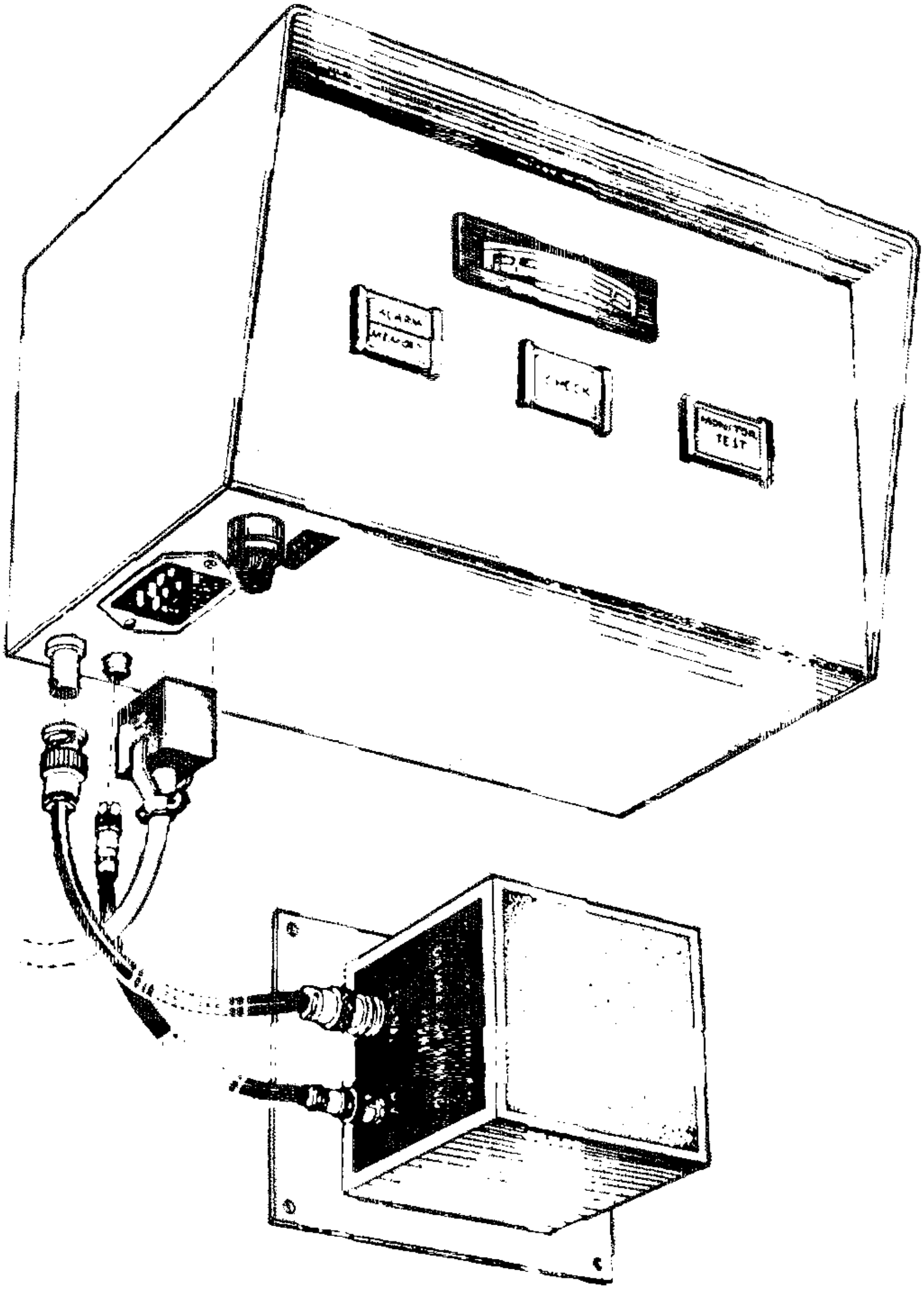

FIG. 10. The L118 wall mounted single probe monitor system. (By courtesy of Nordion International Inc.)

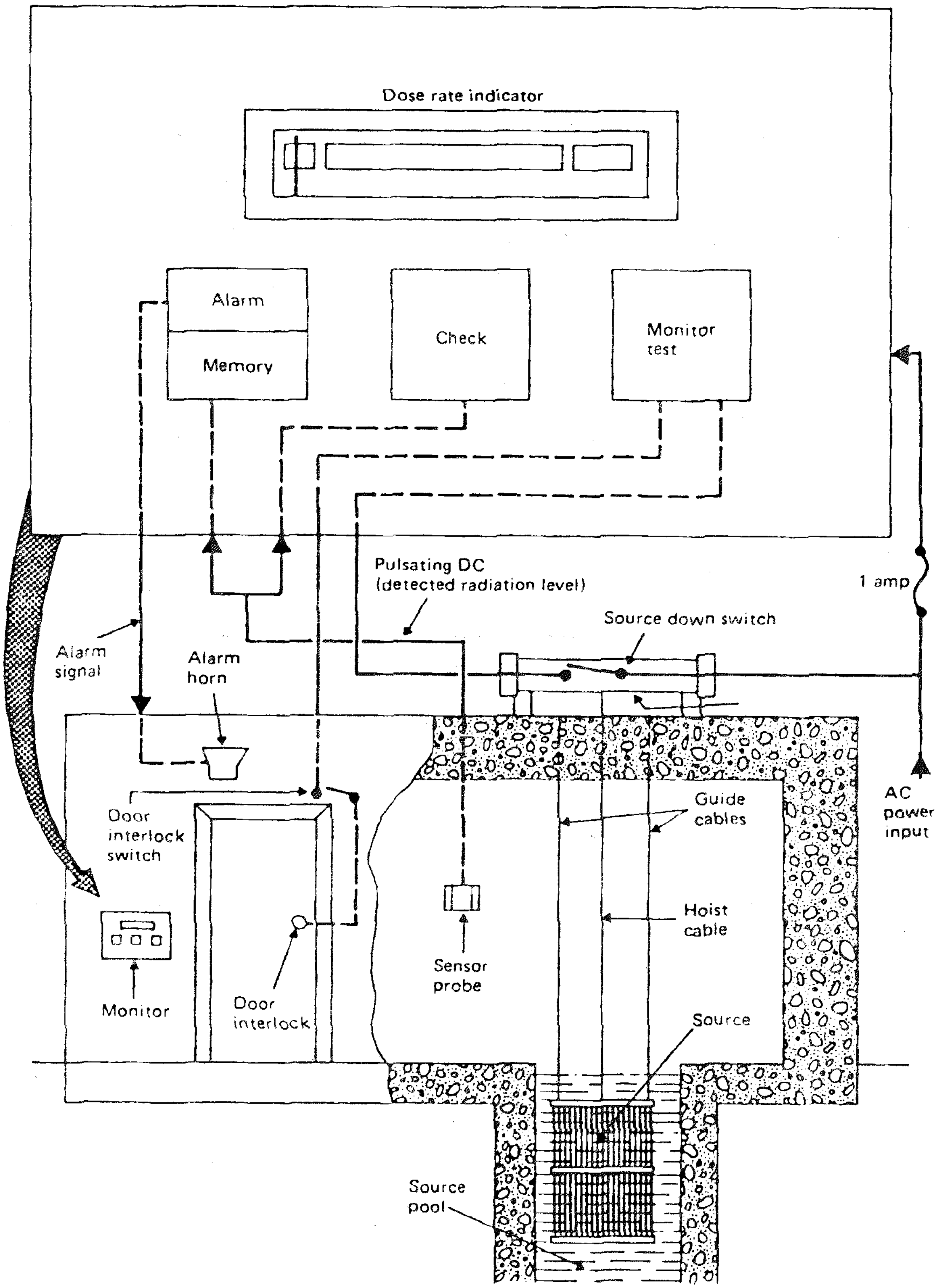

FIG. 11. Schematic diagram of the circuits for the monitor in the radiation room. (By courtesy of Nordion International Inc.)

of the monitor's main features and shows how they are integrated with other safety features.

In order to enter the radiation room, the operator must first press the monitor test button. The counting circuitry in the monitor then causes pulses from the monitor probe as it registers natural background radiation to give a test alarm indication. The test cannot be performed if the monitor is already showing the alarm condition. When the monitor test button is released, the monitor must again indicate normal background radiation before power can be supplied to the key switch that operates the door lock solenoid.

The radiation monitor is also interlocked with the source down microswitch. When the source rack is not fully down (in the storage position), power to the monitor is shut off. This also cuts off power to the key switch that operates the door lock solenoid, thus disabling the access control system and preventing access to the radiation room.

More than five years before the accident, the monitor probe had failed and the probe assembly had been removed. Its cabling remained. Removal of the monitor probe should have disabled the irradiator. However, it was discovered that access could be gained to the radiation room by depressing the monitor test switch and repeatedly cycling the buttons on the panel of the radiation monitor. This method of gaining access became the 'usual' procedure. The access door had not been maintained and had become badly fitting, with the result that it could also be opened by force or by using the blade of a knife to slip the catch (see Photographs 5 and 6). Thus one major safety feature of the design was bypassed.

3.5.3. Automatic safety features

The JS6300 Gamma Sterilizer has automatic safety features for the protection of personnel and the products for sterilization. Safety interlocks require the operator to enter the radiation room and actuate a switch and to close the door before raising the source rack.

The personnel access door can only be opened if the source rack is in the storage position and there are not high radiation fields in the radiation room. If the door is forced open when the source is up, a microswitch behind the door will shut down the irradiator and lower the source.

In the radiation room there is a key switch with a time delay operated by the machine key, to oblige the operator to enter the room before raising the source. The operator is then to make an inspection to ensure that there is no one in the room and that the transport mechanism is in order. When the delay timer is set, a buzzer sounds to warn personnel that the source rack is about to be raised. The operator then has

90 seconds to leave the radiation room, close the door and start the operation of the irradiator from the control panel.

The electricity generation and distribution system in El Salvador has been a common target of attack and power failures have been frequent. In order to reduce the startup time after power cuts and other stoppages, the time delay switch in the radiation room had been replaced with a switch at the control panel.

The radiation room door can be opened from the inside so that personnel cannot be locked in. In addition, an emergency pull cable mounted along the walls of the radiation room and the entrance maze actuates a stop switch that lowers the source or stops the startup operation.

Turning the machine key switch to the off position or pressing the stop button on the control panel will also stop the irradiator and lower the source.

If the irradiator malfunctions or a safety device is actuated, the irradiator is shut down, the source rack is lowered, the red stop light on the control panel lights up and the source transit alarm sounds until the source is in the fully down storage position. Possible causes of an irradiator shutdown include loss of air pressure to the source hoist cylinder, too high a temperature in the radiation room, failure of the source rack to reach the irradiation position in the allotted time, delay in completing the sequence of actions of the pistons, a power failure, or expiry to zero of the overdose time. (The overdose timer should be set to elapse about five minutes after the master timer.)

3.5.4. Administrative controls

In addition to the automatic safety features, there should be administrative controls to ensure that the facility is operated only by trained, authorized operators in accordance with the procedures given in the instruction manual.

In operating the facility, a single machine key is used for resetting faults, operating the irradiator, opening the door and actuating the time delay in the radiation room. A portable radiation monitor should always be attached to this key to ensure that the operator never enters the radiation room without a monitor. This radiation monitor should be checked before each entry of the room with a small test source mounted in the door key switch.

There was no portable radiation monitor attached to the key of the facility and no one knew where the test source was. As is discussed later, there are doubts whether the portable radiation monitor was always used and whether it was used correctly.

3.6. MAINTENANCE

A regular preventive maintenance programme is prescribed in the instruction manual for the irradiator. The number of irradiator shutdowns can be kept to a minimum by following this preventive maintenance programme. A monthly test of all emergency shutdown devices is included in the maintenance programme.

This preventive maintenance programme had not been implemented.

A warning is given in the instruction manual for the JS6300 Gamma Sterilizer that any attempt to modify the installed mechanical, pneumatic or electrical systems of the facility may prove hazardous to personnel and cause extensive damage to the machinery, and that any such modifications must have the written approval of the supplier.

No approval had ever been sought from or given by the supplier for any modifications to the facility.

3.7. OPERATION

The facility should be operated only by trained, authorized personnel in accordance with the operating rules and procedures and emergency procedures given in the instruction manual.

The English language instruction manual provided by the supplier had been translated at the plant; however, the Spanish version was inaccurate and incomplete.

To restart the irradiator after a shutdown, the operator first turns the machine key switch on the control panel to the off position and removes the machine key. Lights on the control panel will indicate the status of the irradiator and whether a fault has occurred. The following procedure should then be followed:

(a) The operator presses the monitor test button on the L118 radiation monitor panel next to the personnel access door and holds it until the monitor alarm sounds. When the monitor test button is released, the alarm stops and the monitor test light remains on, indicating that radiation levels in the radiation room are normal and that the door can be opened with the machine key.

(b) The operator checks the operation of the portable radiation monitor attached to the machine key with the small test source mounted in the door key switch. He (or she) then opens the door with the machine key, enters with the portable radiation monitor, carries out an inspection of the entrance maze and radiation room and corrects any fault that may have caused the shutdown.

(c) To start the irradiator, the operator actuates the 90 second delay timer in the radiation room with the machine key, ensures that no one is in the room and leaves through the entrance maze. The door must be closed and the machine key inserted into the machine key switch and turned to the on position. This raises the source and starts the irradiator.

Each of these operating procedures given in the instruction manual had been circumvented or adapted at the facility, as described in the foregoing sections.

To shut down the irradiator and lower the source, the machine key switch is turned with the machine key to the off position. The machine key can be removed from the machine key switch only when the key switch is in the off position.

3.8. SUPERVISION AND RADIOLOGICAL TRAINING

Initial training in radiation safety, operation of the irradiator, preventive maintenance and maintenance 'troubleshooting' was provided by the supplier at the time of installation of the irradiator. The supplier's normal practice is to train operators during the time taken to install the irradiator in order to familiarize them with its construction, operation and maintenance. Three operators were initially trained to operate the irradiator.

The in-facility course on irradiator operations included instruction in the following:

(a) the purpose of industrial irradiation;
(b) familiarization with the facility (with a tour);
(c) the monitoring system;
(d) the control panel;
(e) auxiliary equipment;
(f) operating procedures;
(g) administrative procedures;
(h) emergency and safety procedures;
(i) maintenance procedures;
(j) contamination detection procedures.

No one at the plant had been given responsibility for radiological protection matters. After the departure, within a year of the facility's commissioning, of the operators who had been trained by the supplier, relevant training was given only orally and informally as part of the instruction of operators in how to operate the facility. There were no effective written local rules. Over the years, awareness of the nature and effects of radiation seems to have dwindled to the point that no one working at the plant appreciated the potential hazards or their scale.

This was the situation in February 1988 when Worker A joined the staff as a maintenance technician. He also became a shift operator of the irradiation facility in September 1988 and received oral training in its operation. He was regarded as showing initiative and resourcefulness in solving the frequent maintenance problems at the facility.

The safety systems at the facility had thus become degraded in several vital respects and the employees did not appreciate the dangers. This state of affairs might be characterized as amounting to 'an accident waiting to happen'. On 5 February 1989, the potential for an accident was fulfilled.

4. THE ACCIDENT

4.1. OVERVIEW

The accident comprised two distinct but associated events. In the first event, on Sunday 5 February (Day 1), three persons were exposed to radiation from the cobalt-60 source elements while manipulating the source rack, receiving potentially lethal doses. Throughout the following week, the management of the plant remained unaware of the seriousness of the accident and the facility continued to be operated normally.

It is believed that the source rack was damaged in this first event, which led to the second event at some time later in the week, in the course of which all the pencils were knocked out of the upper source module. One active source pencil was later found to have remained in the radiation room; the others all fell into the water pool. Although the consequences of this second event were not as great as those of the first, they could potentially have been much more serious, and there are lessons to be learned from both events.

The elevated radiation level in the radiation room (due to the active source pencil) was detected on Day 6 (Friday 10 February). In response to the company's consequent request for help, the supplier sent two of its personnel, who were eventually able to locate the active source pencil and remove it to the pool. It was initially believed that this second event had not resulted in the exposure of any personnel. However, cytogenetic tests made in the course of the investigation of the accident indicated that four workers had received doses in excess of generally applied worker dose limits. The second event is described in Section 4.3.

The investigation of the accident included interviews with the workers and other people involved. As might be expected, there were some minor inconsistencies between the various accounts. The description in the following sections seems to be the most plausible and consistent account of what happened.

4.2. INITIAL EXPOSURES: THE FIRST EVENT

4.2.1. The initiating events

At 18:15 on Saturday 4 February 1989, Worker A began a night shift as operator of the facility. That evening, as usual, he had to deal with a number of power failures and problems with the pistons, but he managed to restart the operation each time. At about 02:00 on Sunday 5 February (Day 1), while he was taking a coffee break, a fault condition occurred which caused the source rack to be lowered automatically from the irradiation position. On returning from his coffee break, he heard the source transit alarm ringing, indicating that the source was neither fully up nor fully down.

He went to the control panel and followed the reset procedure. When this failed to stop the alarm and release the door, he left the control point, walked around through two gates to the other side of the facility and climbed the ladder to the roof where the source hoist is mounted. There, he followed the 'usual' procedure (not that recommended by the supplier) adopted at the facility in such circumstances to return the source to the fully down storage position. He detached the normal regulated pressurized air supply and applied an overpressure to force the source into the fully raised position, in the hope that this would free the source rack and permit its descent to the storage position.

This attempt was also unsuccessful. Since the source transit alarm continued to sound and the hoist cable was still not under tension, he forcibly pulled the slack cable fully out of the hoist mechanism by hand and then fed it back down through the shield. This had the same effect on the microswitch of the hoist cable as though the source rack were in the fully down storage position and finally stopped the alarm.

Worker A descended and returned to the control panel. He found that the (red) general failure light and the source up light were on. He went back to the roof and managed to manipulate the source down microswitch so that when he returned to the control panel he found the (green) source down light on.

In its original design, the facility had a fixed radiation monitor in the radiation room which would have detected radiation from the (still raised) source rack and prevented unlocking of the personnel access door. However, this monitor probe had been removed more than five years before and had not been replaced. To unlock the door, Worker A followed another 'usual' procedure at the facility (not recommended by the supplier) of rapidly cycling the buttons on the L118 radiation monitor panel (which simulated the detection by the fixed monitor of normal background radiation in the radiation room) while turning the key in the door switch (see Fig. 10). At about 02:30 he succeeded in opening the door. Established practice then required waiting for some minutes for ozone to be ventilated from the radiation room. He did so and then switched off the power supply to the facility.

Worker A seems to have been aware that he had not solved the problem of the stuck source rack but not to have appreciated the nature or magnitude of the danger of entering the room. His statements indicated that his impression was that radiation, like ozone, would dissipate and that, as with unpowered X ray equipment, there would be no continuing radiation.

4.2.2. The first entry

Having switched off the power supply, Worker A entered the radiation room with a torch. He did not check the radiation level with the portable radiation monitor. He examined the pistons around the lower of the two levels of the product transport mechanism, noticing nothing out of order. He then removed two fibreglass product boxes from normal positions on the product entry side of the lower level. In the second row, adjacent to the source rack, he found five boxes jammed into the space for four; that is, a nominal total length of boxes of 2.00 m in a floor length of 1.90 m.

Earlier in the shift, when repairing one of the pistons for this second row, he had found that two boxes had cracks, but since they could still hold the products he had not removed them. These deformed boxes may subsequently have disrupted the system for detecting the positions of the boxes, causing the five boxes to be squeezed into the space for four. The deformation of these boxes probably buckled the metal product guides on the conveyor (see Fig. 6), preventing the source rack from being lowered.

Working by torchlight, Worker A removed two of the five boxes, one of which was wedged against the lower of the two source modules in the source rack (see Fig. 5). This took several minutes. The left side of the source rack then became visible. He noticed that the slack cable that he had paid through from the roof was draped over the fixed product guide just above the upper floor level and was obstructing the descent of the source rack.

Unable to free the rack by himself, Worker A left the radiation room about five minutes after his initial entry. He switched the electrical power back on. The failure light (red) was on and the source down light (green) was intermittent. There was no alarm sounding. He then went to seek help.

4.2.3. The second entry

Shortly afterwards, at about 03:00, Worker A returned with Workers B and C, from another department, who had no experience of the irradiation facility. On being asked about any hazard, Worker A assured the others that there was no danger since the machine was switched off. The three men entered the radiation room and proceeded to remove product boxes from the third row on the upper level (adjacent to the source) so that the source rack could be freed from above (see Figs 12 and 13).

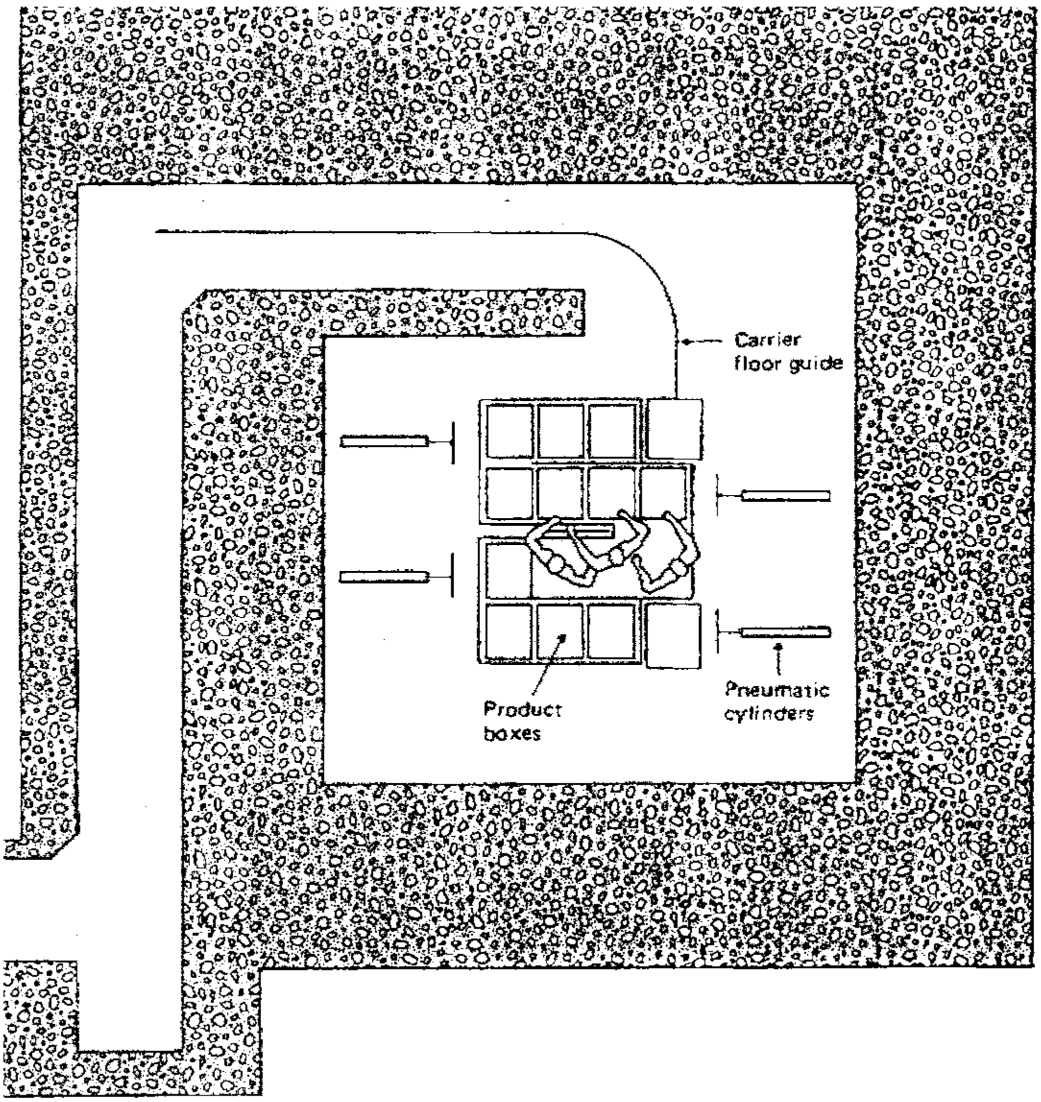

FIG. 12. Plan view of the positions of Workers A, B and C in the radiation room during the accident. (Source: REAC/TS.)

The next phase of the accident was probably when the three workers sustained the largest share of their doses. They would have been moving, but the positions and dose rate contours shown in Figs 13–15 can be taken as indicative of the patterns of exposure. In order to free the source rack they first had to raise it (a mass of about 60 kg) by all three pulling on the hoist cable. Eventually the three men were standing broadly in line on the upper level (Fig. 16). Worker A was in a crouching position with his legs slightly apart and his right leg forward directly in front of the rack. To his right, Worker B had his left leg nearer the source. (The leading leg of each man

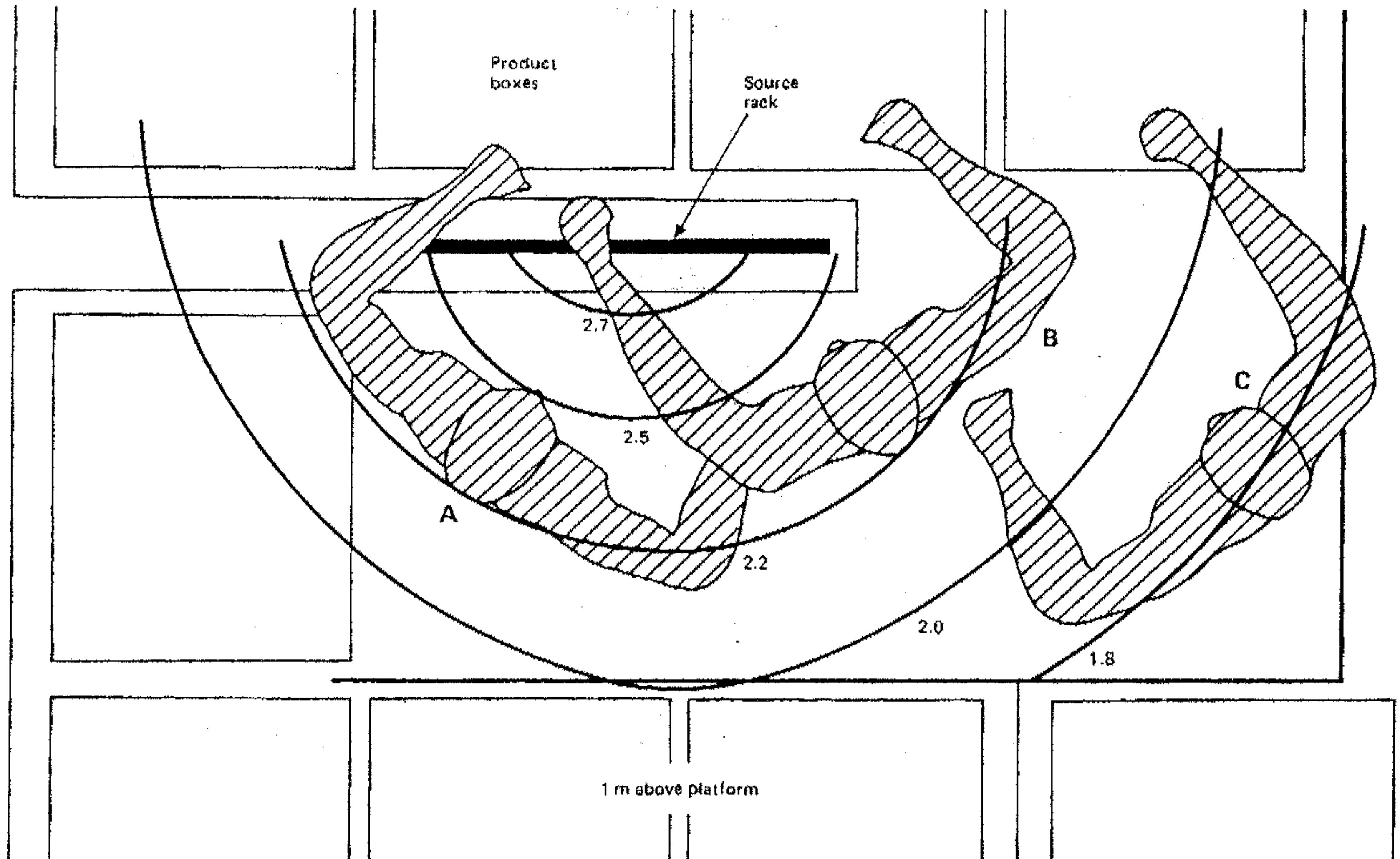

FIG. 13. Plan view of the positions in relation to the source rack of Workers A, B and C during the accident with dose rate contours in Gy·min^{-1}. (Source: REAC/TS.)

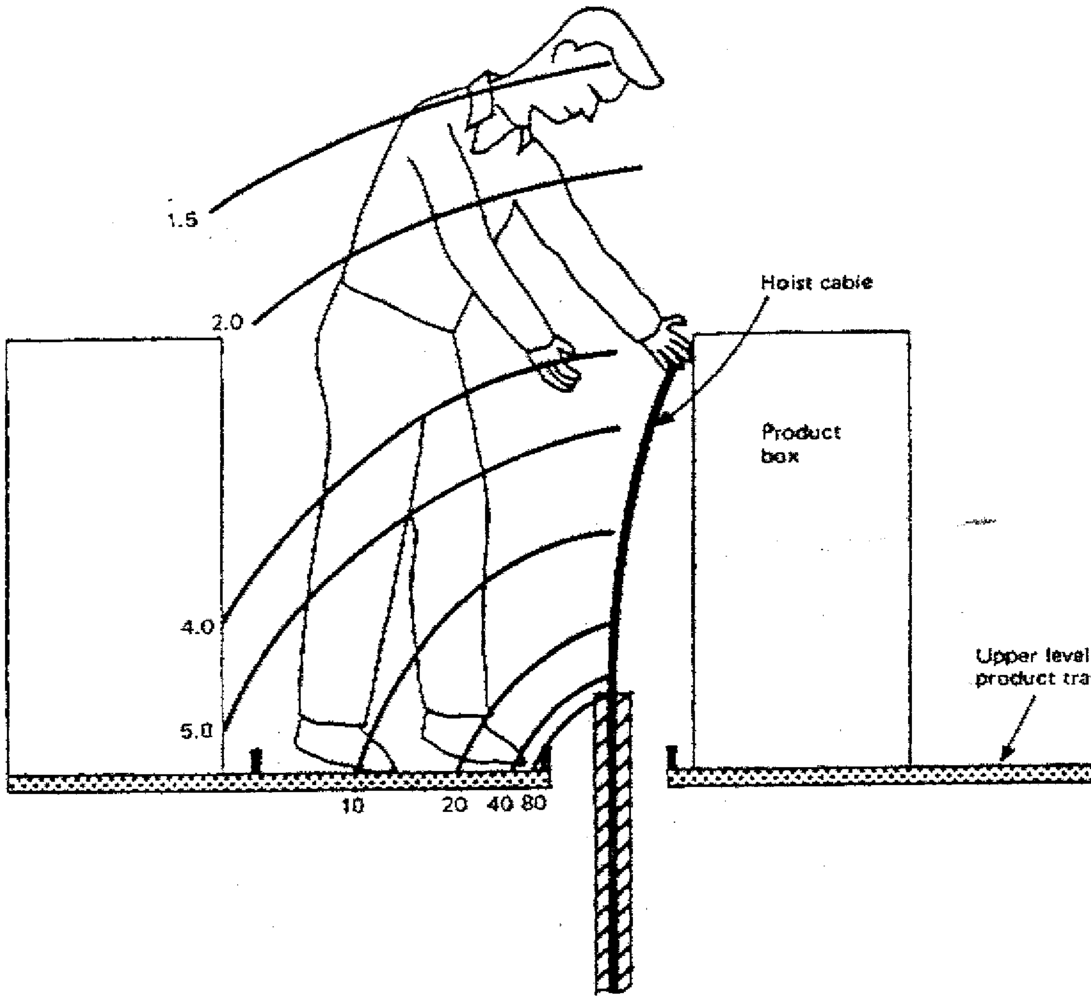

FIG. 14. Dose rate contours for a standing figure: rates in Gy·min^{-1}. (Source: REAC/TS.)

was subsequently amputated first.) Worker C was standing with his left foot on the upper product level and his right foot on a piston. He pulled the hoist cable free while Workers A and B raised the rack.

The three men then paid out the cable over the top of the source rack framework to lower the source rack into the pool. After about two metres of cable had been paid out, the source rack reached the surface of the water, and the men saw the blue glow due to Cerenkov radiation. Worker A was surprised at this and, on fully lowering the source rack, he told his helpers to withdraw quickly. At this point, apparently, he began to suspect that there was some kind of hazard, but not how lethal it was. On leaving the radiation room, Worker B noticed the portable radiation monitor some distance away from the irradiator and asked what its purpose was.

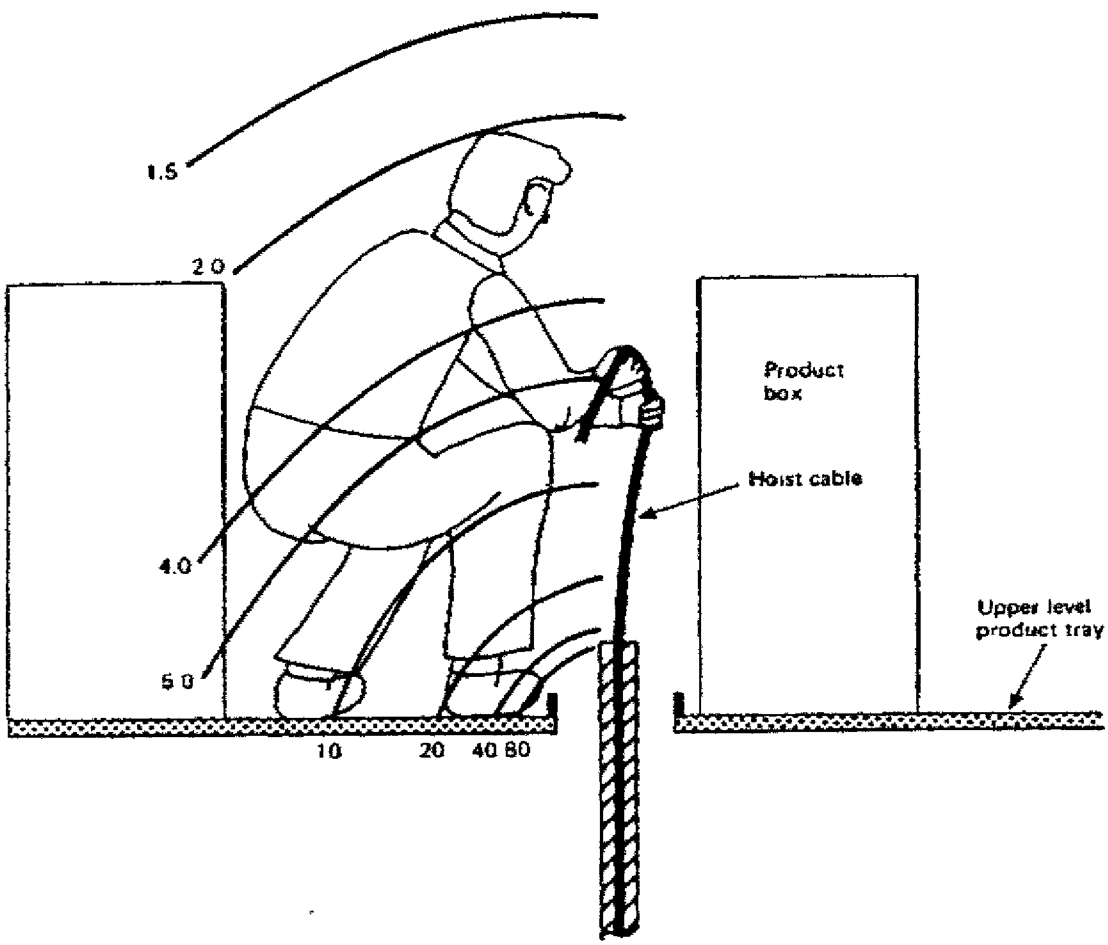

FIG. 15. Dose rate contours for a squatting figure: rates in Gy·min^{-1}. (Source: REAC/TS.)

Worker A replied that it was used for measuring radiation, but that this had not been necessary.

Worker A began vomiting within minutes of leaving the radiation room with the others, having been initially exposed about an hour earlier and being the most exposed of the three. They went outside the building and sat down. He felt increasingly ill. At about 03:30 he began to vomit blood and they went to seek medical help. Since the guard at the gate to the facility was not permitted to leave his post, Worker B helped Worker A about 100 metres to the main road, where they took a taxi to the emergency unit of the Primero de Mayo Hospital. Worker B then began vomiting. Worker C also began to vomit after returning to his work area, and he too went to the Primero de Mayo Hospital. Details of the subsequent medical treatment of Workers A, B and C are given in Section 5.

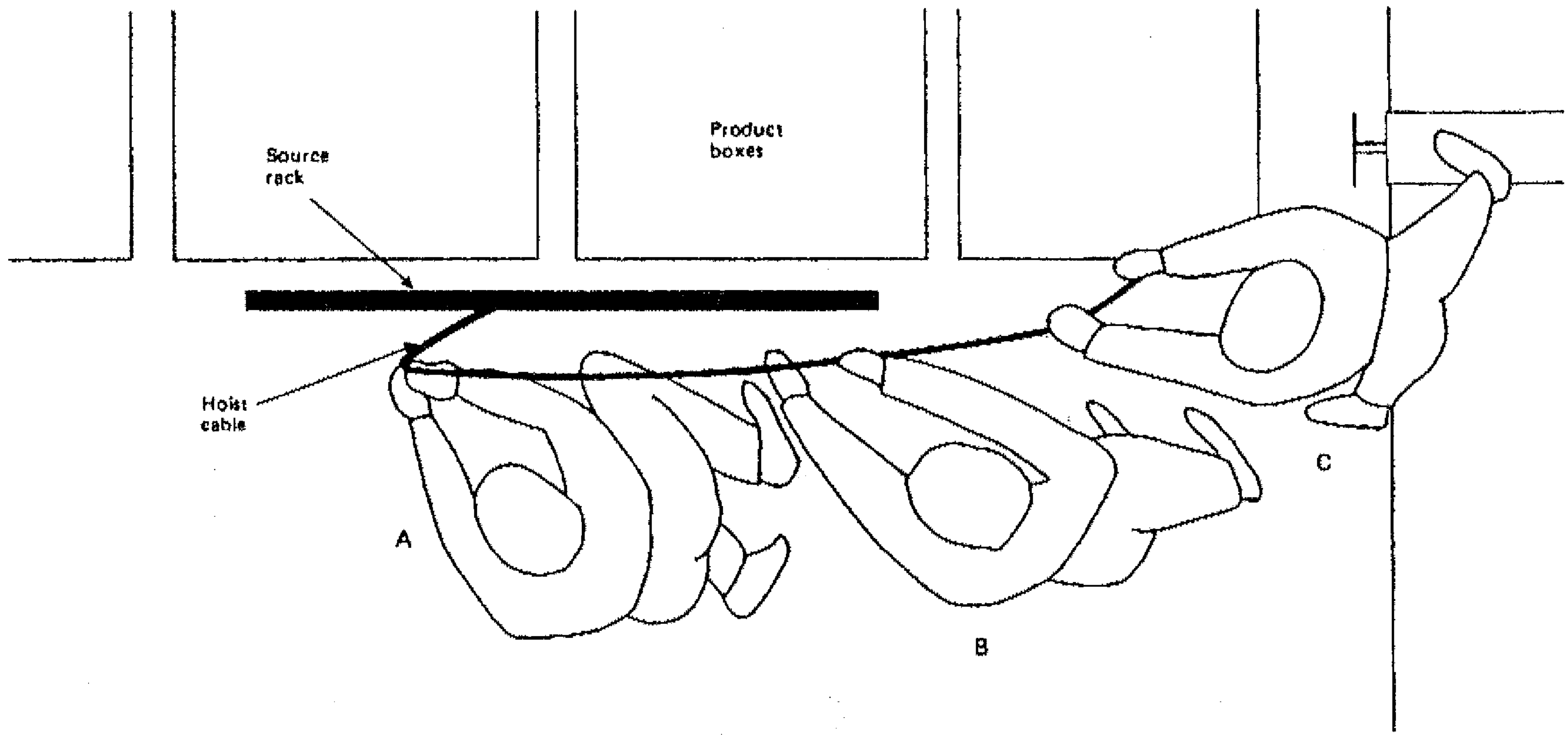

FIG. 16. Plan view of the positions in relation to the source rack of Workers A, B and C while attempting to free the source rack. (Source: REAC/TS.)