AERE - HP Gen 85

HEALTH PHYSICS NOTES FOR STAFF WORKING ON THE HARWELL REACTOR SITE

by

T. A. Tuplin and A. K. Burt

Environmental and Medical Sciences Division,
U.K.A.E.A. Research Group,
Atomic Energy Research Establishment,
HARWELL

January 1974

HL74/252

These notes are largely a synthesis of sections taken from:

- Health Physics Notes for RRD Staff 1960
  by E. M. Flew and J. D. Talbot
- Basic Training in Radiological Safety 1968
  edited by J. Stevenson

suitably modified and updated for the guidance of new personnel and visiting students intending to work on the Harwell Reactor Site.

CONTENTS

1. INTRODUCTION

The Department of Employment and Productivity "Code of Practice for the Protection of Persons exposed to Ionising Radiations in Research and Teaching" states, "It must be impressed on every individual working with ionising radiations or radioactive substances that he has a duty to protect both himself and others from any hazard arising from his work and that he must not expose himself or others to ionising radiations to a greater extent than is reasonably necessary for the purposes of his work". It also states, "The Controlling Authority must ensure that all persons within the establishment who are liable to be exposed to ionising radiations are instructed about the hazards they may meet and about the precautions to be observed". The Sealed Sources Regulations and the Unsealed Radioactive Substances Regulations of the Factories Act have similar requirements.

At Harwell the Environmental and Medical Sciences Division is responsible for providing advice on radiological protection, industrial hygiene, and for providing Medical Services. Industrial Safety is the concern of the Safety Secretariat which is responsible to the director for administrative co-ordination of Health and Safety aspects of work at the establishment. Decontamination and disposal of solid and liquid wastes is the responsibility of the Industrial and Engineering Chemistry Branch of Chemical Engineering Division. The development, supply and maintenance of electronic health physics instruments is looked after by special groups in the Electronics and Applied Physics Division.

Safety Regulations are promulgated as Harwell Notices which must be obeyed by all staff.

The Harwell Safety Committee chaired by the Head of Environmental and Medical Sciences Division, has as members, the Chairmen of Divisional Safety Committees, which help to maintain the standards of conventional and radiological safety in each of the divisions at Harwell. As well as representatives of the various groups in the Division, each Divisional Safety Committee includes representatives from the Environmental and Medical Sciences Division and the Safety Secretariat. Any individual who needs advice on safety matters can approach either his representative on the Divisional Safety Committee, or one of the specialist organisations referred to above.

The control of work involving radioactive materials at Harwell is based on the segregation principle in that all areas in which radioactive materials are handled, or where there are sources of radiation, are scheduled as 'Controlled Areas'. Safety regulations which define behaviour and methods of work in these areas are discussed in more detail in AERE-HP Gen 63 (Safety in Controlled Areas at AERE, Harwell) which is available through DAO's.

Overall responsibility for the safety of operations in Controlled areas is carried out by an 'Area Supervisor' who is usually one of the senior scientists working in the area, and he is appointed by the Division Head. His responsibilities are many and they include training staff in safe methods of working and making sure that they understand and obey the special safety regulations. These special safety regulations for controlled areas concern, for example, the correct wearing of film badges, the wearing of protective clothing, monitoring and issue of transfer certificates before an item can leave certain of these areas, personal discipline - including monitoring, source control, and the raising of special work permits before industrial staff and contractors staff not responsible directly to the Area Supervisor may carry out work in the area.

All Controlled Areas come under the surveillance of the Health Physics Operations Organisation which deals with all aspects of Radiological Safety and Industrial Hygiene. The Health Physics Operations Branch has local offices in many key areas of the site.

Each of these offices is in the charge of a professional Area Health Physicist who is responsible for Health Physics Services over an area of the Establishment usually defined according to its functional interest (e.g. Chemistry Areas, Dido Reactor Area, Nuclear Physics Areas etc.). Each Area Health Physicist leads a team of a Supervisor and a number of Health Surveyors and he or a member of his team is always available for consultation or advice. Their duties include:-

(a) Provision of a Health Physics advisory service and specialist support.

(b) Routine monitoring to prove that control of experiments and work is adequate.

(c) Provision of monitoring instruments.

(d) Provision of emergency services.

The excellent safety record of the Atomic Energy Authority shows that work with very large amounts of radiation can be carried out in complete safety, but this record can only be maintained if all persons pay continual care and attention to necessary precautions.

2. BRIEF DESCRIPTION OF DIDO AND PLUTO REACTORS

Dido and Pluto are highly enriched uranium, heavy water moderated and cooled reactors which operate at a power of about 23MW. The peak flux is about 2×10^{14} n/cm^2/sec.

The Reactor aluminium tank (diameter 6½') contains the Reactor core and the heavy water moderator and reflector. The core which is approximately cylindrical in shape, 2' long and 3' in diameter, consists of 25 fuel elements. The fuel elements are made up of enriched uranium-aluminium alloy tubes. Helium is provided as a blanketing gas above the heavy water.

The Reactor steel tank (diameter 11') contains the aluminium tank and 2' of graphite, acting as a reflector, which surrounds the bottom and sides of the aluminium tank. The sides and bottom of the steel tank are clad on the inside with boral sheet which forms the thermal shield. A 4" water-cooled lead shield surrounds the steel tank.

The biological shield consists of 5' barytes concrete radially and 4'2" underneath. The top shield is complex but consists roughly of 2 mm Cadmium, 4" water cooled lead, 3'3" iron shot concrete and 12" steel.

The Reactors have a number of experimental holes lined with aluminium tubes or thimbles. When not being used for experimental purposes these holes are fitted with standard plugs which are filled with steel shot concrete and have a sheet of boral attached to the inner face. To prevent build up of argon^{41} activity (from argon^{40} which is present to the extent of 1% in air) and nitric acid formation from nitrogen in air, all the experimental holes are purged and filled with carbon dioxide or helium.

The heavy water coolant enters the bottom of the aluminium tank through three 9" diameter pipes and passes up through the fuel elements. It then spills into the tank and leaves through four 7" diameter pipes whose tops are level with the top of the core. The heat is transferred to light water through the heat exchangers in the plant room below the reactor and thence to the atmosphere by induced draught cooling towers.

The reactor power is controlled by cadmium control arms which move up and down between the rows of fuel elements. In addition there are several cadmium vertical safety rods in DIDO and cobalt tipped vertical control rods in PLUTO.

3. UNITS OF MEASUREMENT

To effect control it is necessary to establish units of quantity for radiation; maximum permissible doses may then be fixed in terms of these standard units.

The radiation units in current use are based upon the recommendations of the International Commission on Radiological Units.

The roentgen (R) is a measure of the radiation energy absorbed in air. It applies only to X- and γ-radiation and it is the unit of radiation exposure. The roentgen is defined as that quantity of X- or γ-radiation such that the sum of the electrical charges on all the ions of one sign, produced in air when all the electrons liberated by the photons are completely stopped in air, is 2.58×10^4 coulombs per kg. of air at normal temperature and pressure (N.T.P.). The unit is numerically identical with one electrostatic unit (e.s.u) of charge per 0.001293 g. of air.

The rad is the unit of absorbed dose (D). It is defined as an absorbed radiation dose of 100 ergs/g.. It can be applied to all ionising radiation and to all irradiated materials. The absorbed dose depends upon the properties of the radiation field and upon the properties of the irradiated material; hence the material involved must be quoted. In radiological protection work living tissue of one kind or another is the material of greatest interest.

The rem. Since the biological effect of radiation depends not only on the amount of energy absorbed but also on the type of radiation, a term is required which expresses on a common scale for all ionising radiations the effect of the irradiation incurred by exposed persons. This term is called the 'dose equivalent' and applies to all kinds of ionising radiations. The unit of dose equivalent (DE) is the rem. It is defined as the product of absorbed dose, D quality factor (QF), dose distribution factor (DF), and other necessary modifying factors; thus:-

$$(DE)_{(rem)} = D_{(rad)} \times (QF) \times (DF) \times \ldots\ldots$$

The quality factor (QF) is dependent on the linear energy transfer (LET) of the radiation being considered, i.e., the (QF) takes into account the different rates at which the radiations transfer their energy to the material through which they are passing, eg. the QF for X, γ and β rays is 1 and for 1 MeV neutrons is 10.

The distribution factor (DF) is used to express the modification of the biological effect due to the non-uniform distribution of internally deposited radionuclides.

When considering X- or γ-radiation and the irradiation of soft body tissues, the roentgen and the rad can be regarded as being numerically equivalent for the purposes of radiation protection. When other biological materials eg. bone, are considered, the absorbed dose in rads can be far in excess of the exposure dose in roentgen. Some values of the absorbed dose in bone (for an exposure dose of 1R) for various energy X- or γ-radiations are given below:-

Photon energy	Absorbed dose (ergs/g. bone)
60 keV	293
150 keV	106
1 MeV	93

The curie (Ci) is the unit of radioactivity. It is defined as the activity of that quantity of a radionuclide in which the number of nuclear transformations is exactly $3.7 \times 10^{10} s^{-1}$. The following symbols are used for smaller parts of a curie:-

1 millicurie (mCi) = 10^{-3}Ci
1 microcurie (μCi) = 10^{-6}Ci
1 nanocurie (nCi) = 10^{-9}Ci
1 picocurie (pCi) = 10^{-12}Ci

Connection between Curie and Dose-rate at a Distance

This depends on the type of radiation, the energy of radiation and the distance from the source.

eg. 1 Ci of a 1 MeV γ emitter gives ~6 rems/h at 1 ft. (0.6 rems/h at 1 m.)
and 1 Ci of a β emitter gives ~300 rems/h at 1 ft. (20* rems/h at 1 m.)

* in practice this value will be further reduced due to air absorption.

4. THE EXTERNAL RADIATION HAZARD

4.1 General Description

The external radiation hazard is the risk arising from overexposure of the body to β rays, γ rays or neutrons coming from sources outside the body. β rays cannot penetrate far into the body and therefore only affect the skin. γ rays and neutrons can reach all parts of the body and can therefore affect deep seated organs. In general, no external radiation hazard will arise from α rays because they cannot penetrate the dead cells at the surface of the skin to reach the sensitive skin tissue.

β and γ rays are emitted by radioactive materials, and neutrons and γ rays are produced by Reactors and Accelerating machines such as the Cyclotron and Tandem Generator. Neutrons are also emitted by Ra-Be, Po-Be, Am-Be, and Sb-Be sources.

4.2 Possible Harmful Effects

Beta radiation

Overexposure to beta radiation causes skin burns which resemble ordinary heat burns in appearance. Radiation burns however take some time to develop and are slower to heal, sometimes becoming cancerous.

Gamma radiation and neutrons

The effects of excessive gamma or neutron exposures are best considered in two parts; the acute effects of a massive dose delivered over a few minutes or hours, and the chronic effects which follow long continued uncontrolled exposure to low levels of radiation.

(a) A heavy dose of gamma radiation or neutrons can cause acute radiation sickness; nausea, vomiting and diarrhoea occurring within an hour of exposure. These symptoms are followed by delirium and coma, the illness usually terminating fatally in one to two weeks.

(b) Continuous uncontrolled exposure to low levels of gamma radiation or neutrons can cause damaging disturbances to the bone marrow and in male sperm or female egg cells. The function of the bone marrow is to produce new blood cells of the right kind and in the right quantity. Where this vital function is impaired by excessive radiation the exposed person may develop leukaemia, a condition in which there is uncontrolled overproduction of white cells. Leukaemia is invariably fatal.

Somatic Effects of Acute Whole Body and Skin Irradiations

Effect due to whole body irradiation	Dose Equivalent (rems)	Effect due to skin irradiation
Reduction in lymphocyte count	~ 25	
Temporary nausea	~ 100	
Nausea, diarrhoea within a few hours. Reduction in certain blood cell counts. A few people may die due to failure of blood forming organs.	100-350	
Similar symptoms but more severe. Up to half exposed group may die due to failure of blood forming organs. (LD_{50} dose)	350-500	Loss of hair
Symptoms even more severe. Majority sick within half an hour. Death within 2-3 weeks due to loss of vital body fluids through damage to intestine wall.	500-1000	Redness of the skin
Death within a few days due to damage of central nervous system.	> 1000	Peeling of the skin

4.3 Maximum Permissible Levels of Occupational Exposure

The maximum permissible levels are fixed so that no harmful effect would be expected if the person was exposed to these levels during his whole working life. The levels are not permanent and in the light of fuller knowledge might be amended at any time. Therefore all exposure to radiation should be kept to the lowest practicable level.

Exposed part of body	ADULTS EXPOSED in the course of their work	Individual Members of the public
Whole body, blood forming organs, gonads	5 rems/year* 3 rems/13 weeks	0.5 rems/year
Skin, thyroid, bone	30 rems/year 15 rems/13 weeks	3 rems/year (1.5 rems to thyroid of children <16 years of age)
Exposure of single organs other than skin, thyroid and bone.	15 rems/year 8 rems/13 weeks	1.5 rems/year
Hands, forearms, feet and ankles	75 rems/year 40 rems/13 weeks	7.5 rems/year

* In special cases it may be justifiable to allow the quarterly quota to be repeated in each quarter of the year provided the total dose accumulated in any age over 18 years does not exceed 5(N-18) rems, where N is the age in years.

For individuals aged between 16 and 18 years the annual dose to the whole body, blood forming organs and gonads should ALWAYS be limited to 5 rems in a year. After the age of 18 the relevant limits are 5(N-18) + 10 rems (with an overriding maximum of 60 rems) below the age of 30, and 5(N-18) rems from the age of 30 on.

Women of reproductive age should be occupationally employed only under conditions where the dose to the abdomen is limited to 1.3 rems in a 13 week period. This will normally limit the dose to the embryo during the first two months of pregnancy to 1 rem.

Situations may occur when it may be necessary for a few workers to receive exposures in excess of the recommended quarterly limits. In planned special cases the exposures or intakes of radiative materials may be allowed, providing the dose commitment does not exceed twice the annual dose limit in any single event, and in a lifetime, five times this limit. This type of planned special exposure should not be allowed if the addition of the intended dose to the workers accumulated dose exceeds the amount allowed by the formula $D = 5(n-18)$ (where D is the maximum permissible dose at age N years), or if the worker has previously received abnormal exposures.

Doses in excess of the limits recommended for planned special exposures are acceptable in emergency operations during or immediately after an accident. The justification for this will be the rescue of individuals, the prevention of exposure to a large number of individuals, or the saving of a valuable installation. The I.C.R.P. has not recommended dose limits for this type of situation, but does recommend that individuals should be informed of the risks before they accept such exposures.

4.4 Methods of Protection and Control

General

Clearly there must be careful control of the external radiation dose received. To this end, a number of control arrangements have been introduced which, allowing for some variation in emphasis to suit local conditions, apply to all areas on site. All buildings, plants and machines used for radioactive work are carefully designed to afford as much protection as possible from radiation, e.g. Reactor shields are designed so that the radiation level at their surface is well below the maximum permissible level. Health Physics staff are available to give advice on all problems relating to the handling of radioactive materials or operation of machines producing radiation. Much of the work is carried out under their guidance and they carry out frequent surveys of the radiation levels present in such areas.

Basic Principles of Protection

The Basic methods of protection against external radiation are

(a) the use of the maximum amount of distance between the source and the operator, compatible with the satisfactory performance of the work.

(b) restriction of the period of exposure to the minimum compatible with safe working.

(c) the use of suitable shielding.

(d) restriction of the strength of every source to the minimum necessary for the task in hand.

The protection necessary in any particular situation to ensure that doses are kept below the maximum permissible may be achieved by a combination of one or more of these methods.

(a) Distance

As radiation travels outward from a source its intensity diminishes in accordance with the inverse square law. Under this law the radiation level falls by a factor of 4 each time distance is doubled; trebling distance gives 9 times protection, and so on.

Where the dose-rate one foot from a point gamma source is 100 R per hour, the reading at two feet will be 25 R per hour; the level at ten feet will therefore be 1 R per hour.

Note also that the inverse square law works in reverse i.e. dose rates increase with decreasing distance. Surface dose rates from beta/gamma sources can be very high, for example, a 1 mCi radium source gives

at 1 m. the dose rate is ~0.8 m rad/h
at 1 cm. " " " " 8 rads/h
at 3 mm. " " " " 80 rads/h

1 mCi strontium-90 point source gives a dose rate at 3 mm of approximately 3000 rads/h.

Radioactive sources should therefore never be handled with bare hands, or with gloved hands unless the thickness of the glove is sufficient to reduce the radiation to reasonable levels.

It should be noted that this law does not apply to collimated beams from, for example, open experimental holes on Reactors.

(b) Time

Where conditions are such that continuous working would lead to an individual exceeding the maximum permissible levels it may be necessary to limit the time of exposure. This is usually carried out in practice using a personal integrating dosimeter such as a quartz fibre electroscope, and keeping within a specified maximum dose.

(c) Shielding

β rays - stopped by thin sheets of metal, glass, perspex.

γ rays - require dense materials such as lead and iron. Concrete is also used.

e.g. inches of different materials required to reduce radiation intensity to one-tenth (1 MeV γ rays).

Lead	Iron	Concrete
1.5 inches	2.5 inches	8 inches

Fast Neutrons - these must first be slowed down by hydrogenous materials such as paraffin wax, water, concrete and compressed woods impregnated with resin e.g. jabroc, masonite.

Slow Neutrons - stopped by thin sheets of boron containing material (boral) or cadmium. In the latter case γ rays are produced, their number depending on the number of slow neutrons stopped. In some cases therefore it may be necessary to back up the cadmium shield with a γ shield such as lead.

Control

(a) Colour Coding of Areas

Red Areas are areas in which special precautions are necessary to keep radiation exposures below 5 rem/year

Blue Areas are areas in which the radiation exposures may possibly exceed 1.5 rems per year but are less than 5 rem per year.

These areas are called Controlled Areas and are labelled with the appropriately coloured label.

In practice, additional warning notices are usually erected in the working area to give warning where radiation levels exceed 2.5 mrem/hr.

(b) Use of Work Permits

Work Permits have to be completed for all work in Red Controlled Areas being carried out by industrial employees who are not responsible to the Area Supervisor.

In the case of Contractors Staff, Work Permits are required for any work in any Controlled Areas.

For attached staff the safety arrangements are laid down in AERE Safety Committee Paper No. AERE SC(68)7. This specifies the use of the Personal Record Card which is initiated by the Nominated Officer for the Division. Responsibility is then assumed by the appointed Supervisor whose duty it is to complete the Personal Record Card and arrange safety and health physics instruction as required, as if the attached person were a member of his own staff.

(c) Health Physics Advice and Measurements

All controlled areas are under the care of a Health Physics Officer who is able to give advice on radiation problems. It is his duty to arrange radiation and contamination monitoring as and when necessary and to ensure that the maximum levels of exposure are not exceeded. The final responsibility for the safety of workers does however rest with the person in charge of the work being carried out.

5. THE INTERNAL RADIATION HAZARD

5.1 General Description

An internal radiation hazard arises when radioactive material is taken inside the body. Radionuclides taken inside the body behave in the same way as the corresponding stable elements, e.g. radiocalcium is incorporated into the bony structures of the body in the same way as stable calcium. Since radium and strontium are chemically similar to calcium they are also incorporated into the bony structure. Once incorporated into the bone the strontium or radium is fixed for a long period of time and the tissue in the region of the deposit is therefore continuously irradiated. In the case of strontium-90 (which is normally accompanied by its 'daughter' yttrium-90) the β-particles emitted may irradiate cells within a radius of 0.25 cm. In this case the sum of the energies emitted multiplied by a quality factor for non-uniformity of deposition ($\Sigma E_f(QF)(DF) \ldots$) is 5.5 MeV. Similarly the α-particles emitted by radium-226 and its daughters will irradiate tissues within a radius of 0.05 mm. of the site of deposition and ($\Sigma E_f(QF)(DF) \ldots$) is 110 MeV. Since radium and other α-emitters deposit a much greater amount of energy in a given volume of tissue than do β-emitters, α-emitters cause a much greater amount of damage, and consequently α-radiation emitted inside the body is more dangerous than β-radiation.

The following table compares the maximum permissible body burdens of some of the commonly met, more toxic radionuclides.

Nuclide	µCi	µg
Plutonium-239 (soluble)	0.04	0.64
Radium-226	0.1	0.1
Uranium-233	0.04	4.0
Strontium-90	2.0	10^{-2}
Iodine-131	0.6	4.9×10^{-6}

These amounts are so small that even the largest quantity could not easily be seen with the naked eye.

(Note: 0.04 µCi = 1480 disintegrations/sec. = 200 counts/sec. with the EMI Type AP2 α-probe.)

Even with the most elaborate control arrangements, active substances are sometimes accidentally released, with the result that benches, floor surfaces and items of equipment become contaminated. Where the activity is in dry dust form, or is volatile, some may become airborne.

5.2 Routes of Entry

Ingestion Contamination on surfaces may lead to ingestion of activity through the mouth. Control is a matter of correct laboratory discipline e.g. correct use and removal of gloves, correct monitoring procedures after working in contaminated areas etc.

Inhalation Every operation carried out in laboratory or work-shop is accompanied by the formation of airborne dust. The assessment of the significance of radioactive airborne contamination is a difficult problem due to the influence of many factors such as breathing characteristics (rate of breathing, whether the individual breathes through the nose or the mouth etc.), the size, shape and density of the airborne particles (which will affect the deposition and subsequent metabolism), and the chemical properties of the particles.

Control is very largely based on proper containment and ventilation. Before a job is carried out consideration must be given to the possibility of airborne contamination

Absorption Radioactive contamination may penetrate the skin by diffusion through the skin barrier or via cuts and wounds.

5.3 Possible Harmful Effects

Clearly the period of retention in the body is of the first importance. It is not surprising therefore that, generally speaking, the critical organ for internal radiation is the skeleton, since active materials tending to concentrate in bone are likely to be retained in the body for long periods.

Cancers may develop in bone containing excessive deposits of radioactive material.

Alpha emitters

Alpha emitters are particularly dangerous for the following reasons:

(a) Although alpha particles have only a very short range in tissue, over this limited range they produce intense cell disturbances.

(b) Certain of the long lived alpha active substances are chemically similar to calcium and therefore tend to become deposited in the skeleton.

Beta emitters

The damage trail produced in tissue by a beta particle is longer and less intense than that caused by an alpha particle; moreover, many beta emitters lose their activity fairly quickly (have shorter half-lives than α emitters). A notable exception to this generalisation is Sr^{90} which has a half-life of 28 years.

Gamma Emitters

Gamma rays produce very long, tenuous damage tracks, so that they make a comparatively small contribution to the internal radiation hazard. The damaging effect of a gamma ray emitted by an internal source is dwarfed by the intense disturbances created in tissue by the attendant alph or beta particles.

5.4 Units of Measurement

The maximum amount of internal activity the body can tolerate varies with the isotope. For most active materials, however, the permissible body burden is quite small. The body burden is an amount of radioactive material and is therefore expressed in terms of the curie unit, or rather as number of microcuries(μCi), i.e. in millionth parts of a curie, since very small amounts of activity are significant when they are inside the body.

In practice we are interested in assessing the hazard before the radioactive material gets into the body. To this end, we can measure the concentration of radioactive material in the breathing air and the level of surface contamination.

Air Concentrations are expressed in terms of the amount of radioactive material per unit volume of air, typical units being microcuries per cm^3 of air, or, as this is measured by a drawing a known volume of air through a filter paper which is then counted on a standard counter, in counts per minute on the filter paper per cubic metre of air sampled.

Surface contamination is expressed in terms of the amount of radioactive material per unit area of surface, typical units being microcuries per cm^2 of surface, or, as this is measured by standard counters, in counts per second.

5.5 Maximum Permissible Levels

Maximum Permissible Body Burden

Maximum Permissible body burden of a radioactive isotope is that amount of the isotope which if inside the body will give rise to the maximum permissible levels of radiation to the organ in which it has deposited. Exposure to different isotopes is additive if these deposit in the same organ. Exposure of an organ to radiation from sources inside and outside the body is also additive. Therefore if a person is receiving a significant amount of radiation from radioactive material deposited inside the body, this must be deducted from his permissible exposure to radiation from sources outside the body.

Maximum Permissible Concentration in Air

Maximum permissible levels of air contamination (MPC) air are laid down for each radioactive isotope. If this level were breathed for 40 hours/week, 50 weeks/year for a continuous work period of 50 years, the maximum permissible body burden would at no time be exceeded.

e.g. Radio-isotope	(MPC) air	Disintegrations/min per m^3 of air
Pu^{239}	2×10^{-12} μCi/cc	5 α
Sr^{90}	1×10^{-9} μCi/cc	2,200 β
Co^{60}	1×10^{-8} μCi/cc	22,000 β

Derived Working Limits of Surface Contamination (DWL)

The presence of surface contamination in working areas, on floors, benches, plant and equipment gives rise to the following hazards:

(a) an inhalation hazard if the contamination is disturbed and becomes airborne

(b) an external radiation hazard if high levels of contamination are allowed to build up

(c) an ingestion hazard if the contamination is transferred via the hands to food or to the mouth

On the basis of these hazards the following derived working limits of contamination on inanimate surfaces, skin and personal clothing have been laid down.

Contaminant	DWL $\mu Ci/cm^2$	DWL in counts/sec	
		Instrument	counts/sec
All β emitters	10^{-4}	Standard β probe	5
		End window probe	3
Highly toxic α-emitters e.g. Pu, Ra, Ac, Po	10^{-5}	Standard α probe	
		AP2	3
Other α-emitters	10^{-4}	Standard α-probe	
		AP2	30

In areas where special precautions are taken (Red classification - see 5.6) a relaxation by a factor of 10 on the above figures for inanimate surfaces and protective clothing is allowed.

5.6 Methods of Protection and Control

General

As with the external radiation hazard, very careful control of air and surface contamination must be exercised to prevent personnel from accumulating radioactive material inside the body and thereby being overexposed to radiation from sources inside the body. In areas where this type of hazard is likely to arise, much attention is paid to good ventilation, surface finishes suitable for easy decontamination, etc. Health Physics staff carry out regular monitoring for air and surface contamination, and advise on the precautions necessary during operations likely to give rise to radioactive dust.

Protection

It is obviously desirable to prevent air and surface contamination arising in working areas. To this end, work likely to give rise to contamination (e.g. handling of powdered radioactive material) is, whenever possible, carried out in well ventilated fume cupboards and glove boxes, which contain the activity. The air from these fume cupboards and glove boxes passes through filters, to remove any radioactive material, before being discharged outside the building. In cases where work has to be carried out in areas where high air and surface contamination is likely to be present, (e.g. decontamination and servicing of fume cupboards and glove boxes) much protection can be achieved by the use of protective clothing and breathing apparatus. This ranges from a coverall and respirator to a full pressurised PVC suit.

Control

(a) Colour Coding of Areas

As with the external radiation hazard, the degree of any contamination hazard which may arise in an area is indicated by a colour code.

A Red Contamination Area is one in which the normal procedures in the area may sometimes give rise to hazardous contamination of surfaces and of breathing air.

A Blue Contamination Area is one in which the risk of high levels of contamination is very small.

A White Area is one in which there is negligible risk of radioactive contamination.

(b) Use of Work Permits

The requirements for Work Permits in contamination areas are broadly similar to those for radiation areas. Additionally however they are required in Blue Contamination Areas when the work involves fume hoods and associated ducting, opening active drainage systems or other equipment as specified by the Area Supervisor.

(c) Approved Procedures for Contamination Areas

(i) Minimum protective clothing of a laboratory coat and red toe-capped shoes, or overshoes over non-contact shoes, must be worn in all Red contamination areas. This clothing may also be worn in Blue contamination areas subject to local rules but not in White areas.

(ii) Eating, drinking and smoking are forbidden in all Red contamination areas to minimise the risk of radioactive material being ingested. It is forbidden to carry any food, drink, cigarettes, tobacco, pipes etc. into any Red contamination area. In Blue contamination areas they may be allowed at the discretion of the area supervisor and local Health Physics officer.

(iii) Transfer Certificates (Contamination and Radiation) must accompany any item leaving a Red contamination area for, or through any other type of area unless exemption has been granted by the local Health Physics officer. For a movement out of a Blue contamination area, the receiving or transporting officer is entitled to call for a certificate at his discretion.

(iv) Contamination areas should be regularly cleaned and monitored, and all spills of radioactive material promptly cleaned up to protect persons working in the near vicinity and also to prevent activity spreading to other areas.

(v) The best insurance against the risks associated with contamination lies in the development of a sound personal discipline. It must be remembered too that carelessness on the part of one person may lead to the exposure to contamination of a large number of unsuspecting persons. The above procedures and any other local standing orders should be rigidly adhered to. Washing and monitoring should be carried out after all work in Red contamination areas. Gloves should always be worn for work involving the handling of contaminated articles, equipment etc. Where possible these should be of heavy duty PVC to reduce the risks of cuts and abrasions.

Absorption of activity through the skin is much less likely if barrier cream (available in the Reactor Halls and Active Handling Bays) is applied to the hands before any active work is undertaken.

The most serious type of skin injury is the deep puncture wound, since very little bleeding takes place, but skin injuries of any kind must be treated as important if they are sustained in contamination areas. Wounds should be washed immediately, using copious amounts of running water and the casualty should then report to Medical Services preferably via the local Health Physics officer. If possible, the article causing the wound should be passed to the local Health Physics office for measurement of its contamination.

(d) Health Physics Advice and Monitoring

Monitoring for air and surface contamination is carried out by Health Physics staff both routinely and during individual operations. In Reactor areas monitoring for surface contamination (usually $\beta\gamma$ active) is difficult because of the high gamma radiation background present. Radiation levels which are permissible as regards external radiation do not permit the monitoring for contamination down to the required levels.

For example 2.5 mrem/hr γ radiation gives a count rate of about 200 c/sec on a standard β probe, whereas the maximum permissible level for surface contamination gives a count rate of only 5 c/sec. Thus in a background radiation level of 0.25 mrem/hr (20 c/sec) monitoring for contamination down to 5 c/sec is impossible. In cases where direct monitoring is impracticable, smear testing should be carried out. This consists of wiping an area of 100-200 sq.cm. with a filter paper (~ 5 cm diameter) and counting it either on a standard β probe where the background is low or on a shielded counter.

(e) Medical Tests

Regardless of the route of entry, a large fraction of any substance entering the body is excreted during the following 24 hours. A smaller fraction is excreted once the substance has become established in the body. Thus urine testing can be used to assess the amount of radioactive material inside a person's body.

In practice this is carried out:

(i) As a routine check on control arrangements in Red contamination areas.

(ii) As a post incident check on personnel involved in contamination accidents.

In Reactor areas personnel are selected for urine analysis by the local Reactor Health Physicist on the basis of air and surface contamination levels arising during operations in the area.

(f) Control of Contamination in a Reactor area

In high flux Reactor areas such as DIDO and PLUTO control of contamination is difficult, because:

(i) The occurrence of contamination is largely unpredictable with the result that all operations must be conscientiously monitored despite the discouragement of finding only insignificant levels in most cases.

(ii) The complexity and inaccessibility of parts of plant and handling equipment prevents thorough immediate monitoring and cleaning.

(iii) The large number of transfer operations involving shielded flasks and handling cells tends to spread contamination from one area to another.

Leakage of Gaseous and Particulate Activity from the Reactor

The Dido and Pluto Reactors are not operated at reduced air pressure and therefore if the experimental hole shield plugs do not form perfect seals with their thimbles, a small amount of gaseous and particulate activity can leak out into the Reactor Hall.

The main constituent of this under normal conditions is A^{41}. This is formed by an n γ reaction with the one per cent of A^{40} present in the residual air after gas purging experimental thimbles.

6. THE TRITIUM HAZARD

6.1 General

Tritium is a major hazard associated with heavy water moderated reactors. Its presence in relatively high concentrations (in terms of activity) in the reactor heavy water, coupled with its ease of biological absorption make it worthwhile considering in some detail.

6.2 Tritium (H^3) Data

Tritium emits one β ray, of energy 18 keV per disintegration. No γ radiation is emitted. Radioactive half-life is 12 years.

It is formed by an n γ reaction on the H^2 in the heavy water moderator. At present (1973) the level in the DIDO and PLUTO heavy water is 5 to 6 mCi/cc and is still increasing slowly. Saturation activity at present reactor power should not exceed ~ 20 mCi/cc.

A small amount of tritium is also formed by an np reaction on the He^3 isotope (naturally occurring) in the helium above the heavy water and in the graphite helium system.

Maximum permissible body burden = 1.6 mCi

Maximum permissible air concentration for tritiated water vapour (40 hour week) = 8×10^{-6} µCi/cc

Maximum permissible level in urine (corresponding to 1 M.P.B.B.) = 0.05 µCi/cc

Biological half life = 12 days

6.3 Hazards

Tritium, as tritiated water HTO, can be taken into the body by inhalation, ingestion, or absorption through the skin and becomes distributed throughout the body tissue. In the DIDO and PLUTO Reactor Areas this can occur in the following ways:

(a) Exposure to the air of irradiated heavy water or surfaces contaminated with heavy water can lead to tritiated water vapour being inhaled or absorbed through the skin.

Consider for example a stagnant air space with a temperature of $80^{\circ}F$ and a relative humidity of 80% and where there is a heavy water leak such that the water vapour content of the air is essentially all heavy water.

Heavy water concentration in air = 20 mg/litre

At 5 mCi/cc of heavy water the tritium content of the air

$$= \frac{20 \times 10^{-3} \times 5 \times 10^{3}}{10^{3}} \ \text{Ci/cc air} = 10^{-1} \ \mu\text{Ci/cc}$$

$$= \underline{\geq 10{,}000 \text{ MPCs tritium}}$$

(b) Ingestion, arising from eating, drinking or smoking in areas which may be contaminated with irradiated heavy water.

(c) Absorption through the skin due to direct contact with irradiated heavy water.

6.4 Methods of Protection and Control

(a) All spills of irradiated heavy water should be immediately mopped up with cotton wool (wearing rubber gloves) which should be placed in an air tight container.

(b) All bottles, drums etc. containing irradiated heavy water should be air tight.

(c) Protective clothing contaminated with irradiated heavy water should be sealed in air tight containers and specially labelled with a tritium warning.

(d) Pressurised PVC suits or PVC suits and airhoods and rubber gloves must be worn by all personnel engaged in any work in breaking into the Reactor Heavy Water or Helium Systems.

As a small amount of tritiated water vapour passes through PVC clothing it is necessary in addition to make a complete change of clothing. As a rough working guide a protection factor of ~ 10 may be assumed for one hour's work in an unpressurised PVC suit and airhood or self-air set and a corresponding factor of ~ 100 for a pressurised PVC suit.

(e) Personnel accidentally splashed on the skin with irradiated heavy water must wash the affected part immediately and report to the local Health Physics Office.

(f) Protective clothing (including PVC) splashed with irradiated heavy water should be changed as soon as possible.

(g) Jobs involving a tritium hazard must be covered by a member of the Health Physics Operations staff who can advise where necessary and who will record relevant details of the operation.

(h) A number of staff are on routine urine analysis for tritium. The local Health Physicist or Health Physics Supervisor will request additional staff to submit urine samples as required.

7. MONITORING INSTRUMENTS

7.1 Three main forms of radiation monitoring instruments are available.

(a) Personal monitors

(b) Portable monitors

(c) Installed monitors

7.2 Personal Radiation Monitors

Film Badge

The Film Badge is sensitive to beta, gamma, X-ray and slow neutron radiation. The response of the unfiltered photographic emulsion to gamma radiation is energy dependent and it is largely unaffected by neutrons. Filters in the film badge holder make it possible to determine doses due to radiations of different types and energies. The specification for the holder is that it should be capable of estimating exposure to the following types of radiation, both singly and in mixtures:

X and gamma radiation in the energy range 10 keV to 3 MeV.

Beta radiation in the energy range 0.2 MeV to 2.5 MeV. (The dosimetry of beta radiation of energies 0.2 to 0.5 MeV is imprecise).

Thermal neutrons

The measuring area is divided into six areas as follows:

Open window area

Thin plastic (45 mg/cm^2)

Thick plastic (250 mg/cm^2)

Dural (0.1 cm)

Tin/lead (0.07 cm + 0.03 cm)

Cadmium/lead (0.07 cm + 0.03 cm)

The general purposes of the filters are:

Thick plastic to separate contributions from photons and electrons

Open window and thin plastic for obtaining effective electron energy and the appropriate correction factor

Dural and tin/lead in conjunction with the thick plastic filter for obtaining the corrected photon dose.

Cadmium/lead in conjunction with the tin/lead for obtaining the thermal neutron dose.

To cover the range of doses encountered in normal work and those which may occur in a radiation accident it is necessary to use two emulsions; a sensitive emulsion on one side of the film base and an insensitive emulsion on the other. The film can measure doses in the range 2 mrad to 10 rad on the combined emulsion and up to about 1000 rad in the less sensitive emulsion.

The film badge results are taken as the true dose received and a personal radiation record card is maintained for each employee. It is therefore of the utmost importance that the dose indicated by the badge is representative of the actual dose received. The recorded dose will be inaccurate if the badge is worn in the pocket, not worn at all, contaminated or left near a source. Spurious blackening may also occur if the film badge wrapper is damaged, or is exposed to excessive heat or moisture, or to certain chemical vapours such as mercury

7.2.2 Neutron Monitoring Track-Plates

This dosimeter consists of a polythene film sandwiched between two layers of sensitive nuclear photographic emulsion. Fast neutrons give rise to knock-on protons in the polythene and the emulsion and these protons produce tracks in the emulsion. The threshold energy for producing recognisable tracks is probably about 0.5 MeV. A dose of 1 rem produces 130 tracks in an area 21 cm × 94 μ. The monitoring system can measure doses from 0.05 rem to 100 rems.

7.2.3 Quartz Fibre Electroscopes (Q.F.E's)

These monitors have small ion chambers (air equivalent walls). The loss of charge from the ion chamber is measured by an integral quartz fibre electroscope. Gamma sensitive Q.F.E's are available having full scale deflections varying from 0.2 rad for the most sensitive models to 50 rads for the least sensitive models. Energy response is reasonably flat from 40 keV to 3 MeV.

7.2.4 Meter Indicating Dosimeters (AERE Type 1757 etc.)

These monitors have small ion chambers (air equivalent wall) and a valve electrometer circuit to measure loss of charge. The most sensitive model has a full scale deflection of 200 mrads. The response is reasonably energy independent down to 60 keV. Q.F.E's and meter indicating instruments enable a minute to minute watch to be kept on a person's exposure and are very useful in areas where high γ levels are likely to arise for short periods, e.g. during unloading operations from Reactors.

7.2.5 Audible Alarm Dose-rate Meters

These instruments are pocket sized gamma radiation monitors which indicate the dose-rate by emitting a 'peep' from a built in speaker at a frequency which is dependent on the dose-rate. Two versions of the instrument are available, both emit a continuous note at about 1 R/h dose rate.

(a) A low level instrument which emits a series of 'pips' whose repetition frequency increases with increasing dose rate. At 6.5 mR/h for example the 'pip' frequency is 1 per second and at 1R/h it is 90 per second.

(b) A high level version which starts 'peeping' at about 120 mR/h. This instrument must be worn by persons entering the Reactor Halls. If the instrument starts to 'peep' the following action must be taken:

> Move away from the source of radiation; obtain a suitable radiation monitor and measure the radiation level when re-entering the radiation area. Further action should be taken as necessary to reduce the radiation levels.

7.2.6 Criticality Dosimeter

Persons who might receive heavy single radiation exposure as a result of a reactor or other criticality accident are issued with a criticality dosimeter. This consists of a small plastic locket containing a thermoluminescent dosimeter (T.L.D.), a sulphur disc, an indium foil and two gold foils separated by a cadmium foil. This combination measures neutron dose over a wide energy range and also gamma dose.

In addition to this quantitative function the indium foil serves also as an exposure indicator which facilitates early identification of exposed personnel by use of a simple gamma probe. Monitoring these dosimeters would be a priority operation after a criticality incident. For the same reason indium is incorporated in all body film badge holders and in AERE security passes.

The criticality dosimeter is usually worn attached to a standard film badge which itself would also be used to measure the gamma component of a criticality dose.

7.3 Portable Radiation Monitors

Beta-gamma Monitor AERE Type 1349 is an ionisation chamber (air equivalent wall) type of dose-rate meter which reads from 0 to 1.5 R/h in three ranges with a substantially energy independent response for gamma radiation down to 65 keV. It is sensitive to beta radiation when the bottom flap is opened to expose the 30 mg/cm^2 beta window. The beta response is energy dependent. For example, at 0.8 MeV beta energy it indicates about 10% of true dose-rate and at 2.25 MeV it indicates about 30% of true dose-rate.

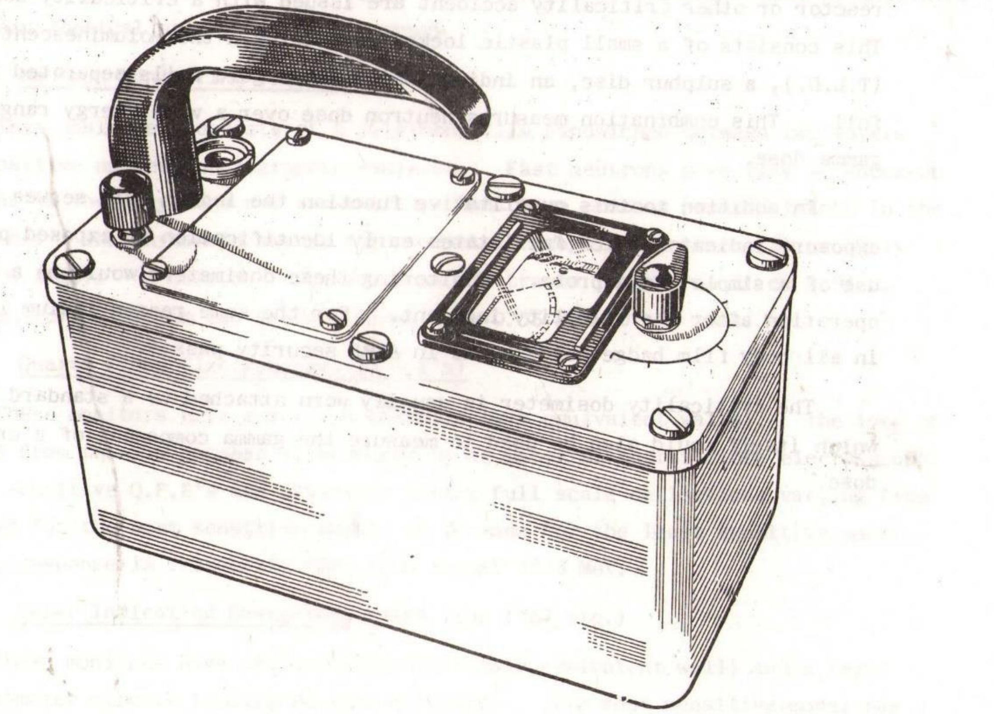


Fig. 1. General View - Meter Survey Slow Neutron 1399A

Beta-gamma Dose-rate Monitor T.0030

This is also an ionisation chamber type of dose-rate monitor which reads from 0-4 R/h in 4 ranges. In addition a range doubling switch is fitted which gives a total coverage of 0-8 R/h. The gamma response of the instrument is substantially energy independent between 6 keV and 3 MeV, but the front cover of the ionisation chamber should be removed to expose the thin (7 mgm/cm^2) window when measuring gamma energies below 50 keV. β radiation can also be detected through the thin window; the response is such that the observed dose rate is about 50% of the true dose rate at about 1 MeV energy. In general it is recommended that the observed β reading should be multiplied by a factor of 2 to obtain a better estimate of the true dose rate.

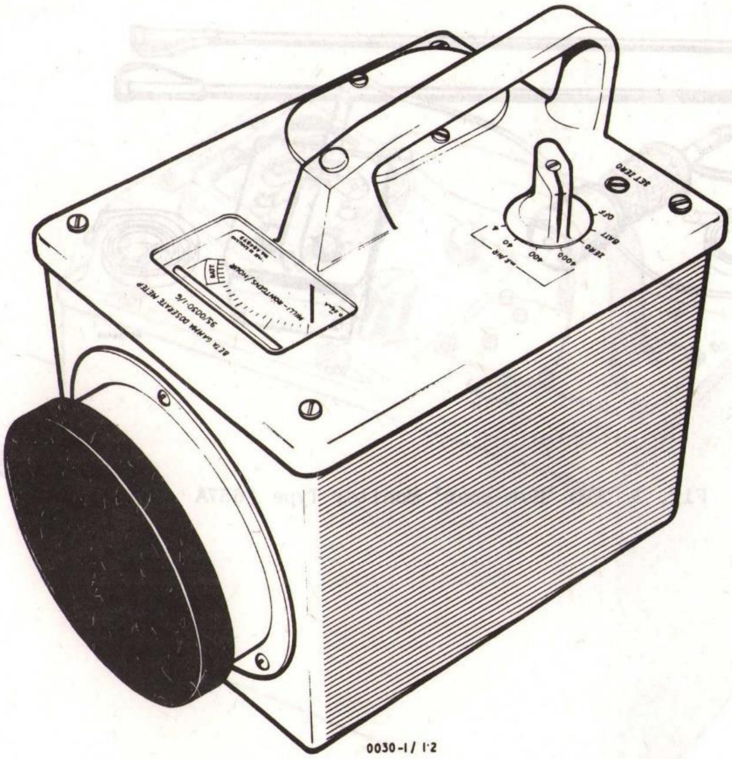


Fig. 2 Beta Gamma Doserate Meter 95/0030-1/6

The AVO Hot-Spot Monitor Type 1657A is a portable battery operated instrument for the measurement of local 'hot-spots' of beta or gamma radiation. The dose rate is displayed logorithmically on the meter covering the range from 0.05 R/hr - 100 R/hr in three decades.

The gamma energy response is much the same as for the AERE Type 1349 but with the chamber cover removed its beta response is better than that instrument. For example at 0.8 MeV beta energy it indicates 55% of true dose-rate, and at 2.25 MeV beta energy it indicates 80% of true dose rate.

Provision is made for remote measurement by means of extension rods and a flexible connector to allow up to 13 ft between the ionisation chamber and the indicator unit.

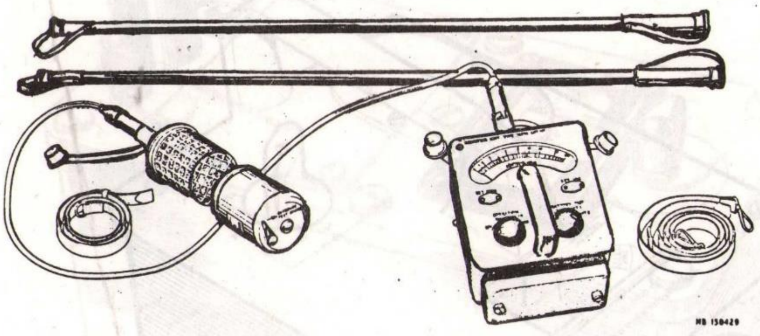


Fig. 3 AVO 'Hot-spot' Monitor Type 1657A

Slow Neutron Monitor AERE Type 1399 is similar to the AERE Type 1349 both in appearance and in its method of operation. Its green handle distinguishes it from that instrument. It can measure slow neutron dose-rates from 0 to 150 mrems/h in two ranges. The ionisation chamber is aluminium with a boron-10/graphite inner coating. Slow neutron capture in the boron-10 produces alpha particles which ionise the air in the chamber. It gives better than 100:1 discrimination against gamma radiation.

Fast Neutron Monitor AERE Type 1645 is a ratemeter type of instrument. The detector is a proportional counter having polythene cells and an argon-methane filling. Knock-on protons from the hydrogen in the polythene lining (n,p) reaction ionise the gas in the counter. It indicates from 0 to 400 counts per second in three ranges. 1 count per second is equivalent to 10 mrem per hour. When properly adjusted the monitor is very insensitive to gamma radiation. Some faults can cause it to become gamma sensitive.

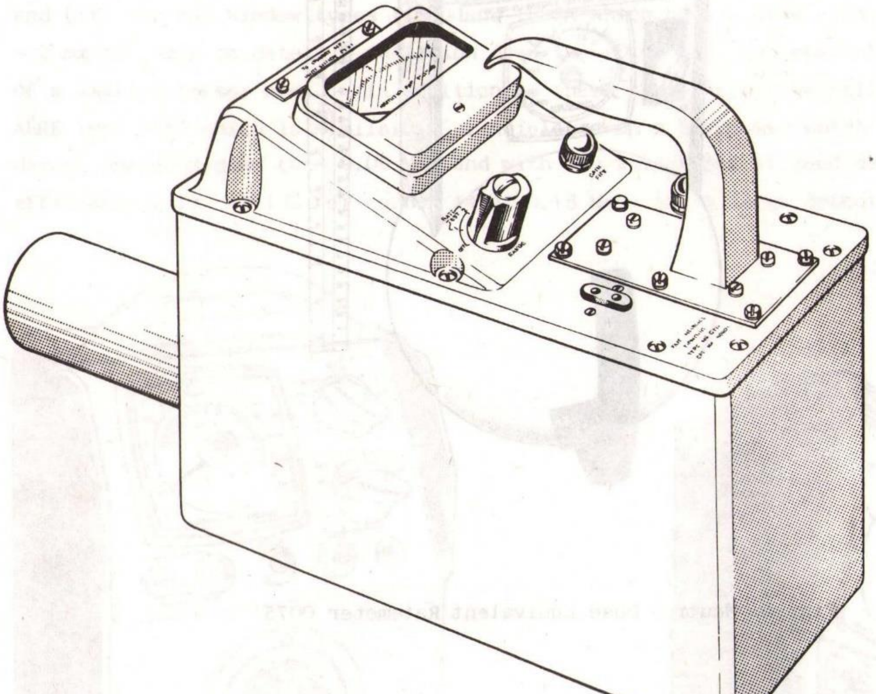


Fig.4 PORTABLE FAST NEUTRON MONITOR TYPE NE O46

Neutron Dose Equivalent Ratemeter Type 0075 is a portable unit for the measurement of neutron dose equivalent rate in the range 0.5 m rem/h to 1 rem/h for neutrons of energies between thermal and 7 MeV.

It consists in principle of a helium filled proportional counter sensitive to thermal neutrons, surrounded by a complex spherical moderator designed to give a near uniform response within the working energy range

Discrimination against γ radiation is > 3000:1 at exposure rates up to 1R/h. At greater rates the discrimination is less but is typically > 1000:1 at 10R/h

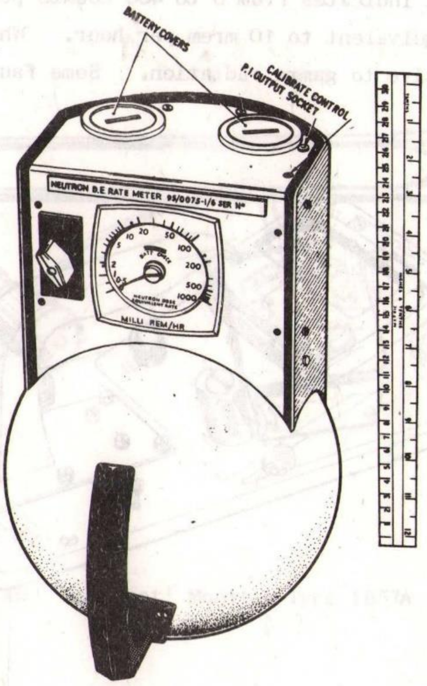


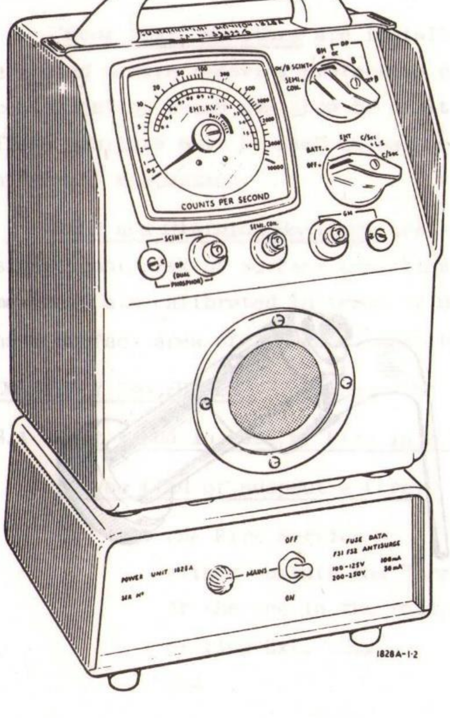
Fig. 5 Neutron Dose Equivalent Ratemeter 0075

7.4 Portable Contamination Monitors

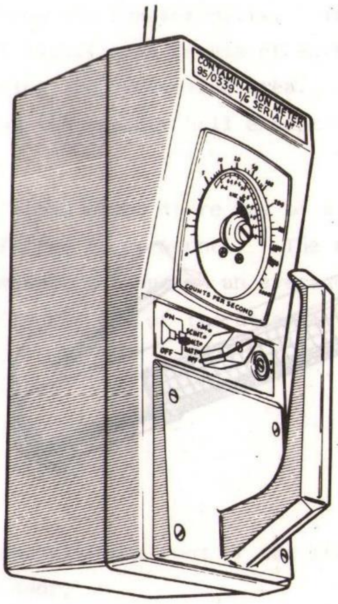
Surface Contamination Monitors AERE Types 1828A and 0339 are rate-meters that can be used to measure alph or beta contamination when connected to the appropriate detectors.

Alpha detectors are normally zinc sulphide coated screens in which the alpha particles produce scintillations. A photomultiplier detects the scintillations and provides pulses for the rate meter. Light is kept from the light sensitive screen by a thin aluminised membrane (about 1 mg/cm^2), which is very easily damaged and must therefore be handled with great care. Alpha probes will also detect gamma and neutron radiation in certain conditions. The alpha probes available are Types AP2 or AP3; Burndept Type 111; etc with detection efficiencies better than 15%, all are interchangeable with the rate-meters T.1828A and 0339.

Geiger counters are normally used for β contamination monitoring. The standard probes are (i) the side window (B12) 1021, 1828A and 1828B which have glass envelopes ~ 30 mg/cm^2 thick and which will not detect β radiation with energies below 0.3 MeV and (ii) the end window types 1150D and 1828A which have a thin mica window only ~ 2 mg/cm^2 able to detect β radiation down to ~ 0.06 MeV, but which has the disadvantage of a small detector area. In addition to these there is a β scintillation detector, AERE type 1667 which is similar in principle to an α probe and which will readily detect energies down to ~ 0.06 MeV and with the advantages of good detection efficiency (e.g. 10-15% for carbon 14 at 0.15 MeV) and a large detector area.



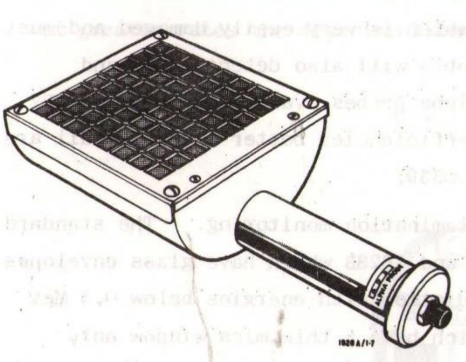
Type 1828A



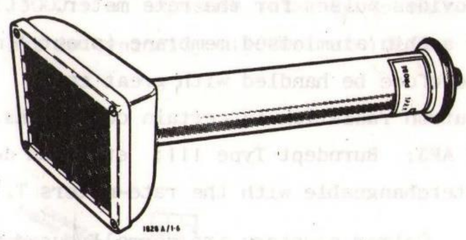
Type 0339

Contamination Probes

(a) α-Scintillation Probes

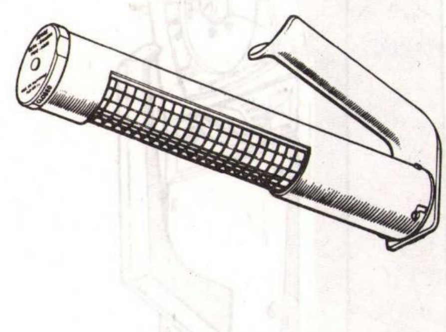


Type AP3

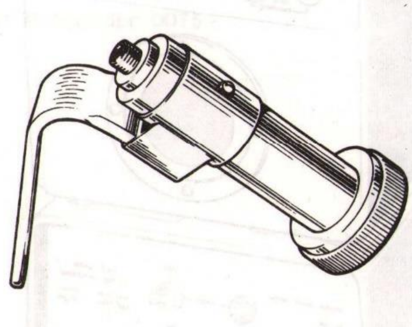


Type AP2, DP2, BP5

(b) GM Probes



Side Window Probe



End Window Probe

7.5 Installed Monitors

Local Gamma Alarms are distributed around the reactor and are preset to trigger at levels dependent upon the nature of particular local hazards. It is advisable to ascertain the siting and setting of these local alarms so that the significance of a warning can be assessed.

High Gamma Alarms are located at certain critical sites - including the reactor halls. They are set to trip at 3 R/hr and are linked to a Site Annunciator Panel system which alerts other Reactor Site areas.

Gas Monitor, Type 1844 Although primarily intended for the detection and measurement of tritium as water vapour (HTO) in air, these monitors respond to other radioactive gasses including elemental tritium and gaseous fission products. In the Reactor Halls these monitors are connected to several sampling points any one of which can be monitored at a given time.

Airborne Dust Monitors are used for the detection and estimation of radioactive dust in the air by drawing air through a filter paper. By metering the volume of air and measuring the level of activity on the filter paper the activity per unit volume of air can be estimated. In those cases where iodine or other halogens are likely a special charcoal impregnated paper can be used to improve efficiency.

The Beta Particulate Monitor Type 1615 uses a long continuously moving filter paper strip which passes successively under an air sampling head and a shielded end window geiger counter. The level of activity is continuously measured and recorded and an alarm can be set to trigger at any desired level. A given point on the paper strip takes about ten minutes to pass from the sampling point to the detector.

'Door Post' Monitors are installed at the exits from the Reactor Halls. These are used before removing protective clothing to detect significant levels of surface contamination which can then be dealt with before leaving the controlled area. These monitors must be used on each occasion of leaving the reactor hall except during a 'scram' evacuation.

Hand and Clothing Monitors are sited adjacent to areas where there may be a significant risk of surface contamination being transferred to personnel. The hand monitors are calibrated in terms of DWL surface contamination based on an average hand surface area of 300 cm^2. Clothing is monitored by the use of the attached probes.

8. EMERGENCY PROCEDURES

8.1 What to do in case of Fire in a Reactor Hall

If you find or suspect a fire:

1) tell the Fire Service -

either operate the "break-glass" alarm opposite the foot of the stairs,
or the one in the road outside the main door,
or ring Ext. 2222,
and

2) tell the reactor Control Room -

ring Ext. 5057 or 5214,

then -

3) fight the fire with hand extinguishers and close smoke doors.

If the fire might hazard staff:

1) sound the nearest rotary alarm loudly,

and -

2) ask the Control Room to instruct staff in the building to evacuate the shell and assemble in the unaffected Reactor Active Handling Bay.

If you hear a fire alarm sounding:

1) sound the nearest alarm to you,

then -

2) evacuate quickly to the unaffected Reactor Active Handling Bay through the nearest exit.

8.2 Scram Warnings

All staff on the reactor site are reminded of the actions to be taken in the event of a reactor Scram sounding. If you are in DIDO or PLUTO containment building or associated workshops or offices when your Scram siren is sounded you must run to the Handling Bay of the other reactor, avoiding contact with other people to avoid spreading contamination. On arrival, report to the Health Physics and Operations staff, who will be waiting to receive and monitor you.

If you are anywhere else on the reactor sit, except the unaffected reactor, go to Building 521, keeping as far from the affected reactor as possible.

INTERNAL DISTRIBUTION

Dr. N. G. Stewart	A.E.R.E.
Miss E. M. Flew	"
Mr. I. S. Jones	"
Dr. T. A. Hall	"
Mr. T. G. Smith	"
Mr. D. J. Taylor	"
Mr. D. H. C. Harris	"
Mr. A. K. Burt	"
Env. & Med. Library	"
Mr. T. A. Tuplin (250 copies)	"