CONTROL OF RADIOACTIVE POLLUTION IN THE ENVIRONMENT
OF THE CERN ACCELERATORS

F.A. Prantl and J. Baarli

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CONTROL OF RADIOACTIVE POLLUTION IN THE ENVIRONMENT OF THE CERN ACCELERATORS

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SUMMARY

This report gives a brief review of the methods developed and some results obtained concerning the environmental monitoring of radiation and radioactivity on the CERN site. Systematic investigations of these problems are necessary in order to ensure that the radiation safety precautions are adequate and that the influence on the environment is known and remains within the prescribed limits. This report shows that air, dust and effluent water radioactivity from the CERN accelerators is barely detectable at a distance of 350 m from the accelerators and represents a very small contribution to the environmental radioactivity of the surroundings.
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1. INTRODUCTION

A great deal of literature and many recommendations exist on the control of radioactive pollution in the environment of nuclear reactor installations\textsuperscript{1,2}). Little is known, however, about induced radioactivity discharged from high energy accelerator installations.

In view of the exploitation of high energy accelerators with increased intensities and ejection rates the influence of their operation with regard to radioactive pollution of their environment has been investigated.

The purpose of the present paper is to give an outline of these investigations together with the aspects of procedures and equipment used for the environmental radioactivity control at CERN.

During accelerator operation induced radioactivity is produced from nuclear interactions between escaping primary, secondary and stray radiation and surrounding materials. Much of the irradiated material remains within the accelerator enclosures without contributing to the radioactivity of the open environment. These are for example machine parts, concrete shieldings, and recycled cooling water of magnets, RF cavities, targets and beam dumps. Others, like activated soil from the accelerator earth shielding, radioactive dust, gases, and particulate matter suspended in air can spread into the environment via ventilation or drainage systems.

The main production areas of induced radioactivity are where internal or external beam losses occur: inside the accelerator buildings, target areas, ejected beam areas, and locations of beam dumps.

Stray radiation escaping through accelerator shieldings can activate the environment. Because at CERN its intensity is low and rapidly decreases with increasing distance from the accelerators, its contribution to the environmental radioactivity levels remains small and was found to play a role only in soil activation of the earth shielding near target areas of the proton-synchrotron\textsuperscript{3}).
Systematic studies of the influence of high energy accelerator operation on the environment have been carried out at CERN since 1968\textsuperscript{4}). They consisted in measuring the radioactivities of air, drainage water, precipitation, sludge accumulations in drainage shafts and effluent streams, and soil samples. The measurements are analysed taking into consideration operating conditions of the accelerators, stray radiation, meteorological, hydrological and local topographical conditions.

The information obtained by these studies formed the basis for establishing a continuous routine environmental radioactivity monitoring programme at CERN in 1969. The objectives of this programme are:

(a) Determination of total levels of environmental radioactivity with regard to the existing safety norms.

(b) Determination of various isotope concentrations contributing to the total activities.

(c) Prevention of radioactive pollution and accumulation in the environment.

(d) Maintaining good relationship between the Organization and the surrounding communities.

2. MONITORING PRACTICES

Meteorological data

For the interpretation of the environmental radioactivity measurements the meteorological conditions play an important role and are taken into account. This includes meteorological observations, synoptic data and recording of temperature, air pressure, humidity and precipitation.

Meteorological observations and synoptic data are representative of a much larger region than the Laboratory site and therefore are obtained from the neighbouring meteorological station at the airport Genève-Cointrin. Temperature, air pressure, humidity and precipitation are recorded in a station on the Laboratory site. This was found necessary because of possible local variations and of the continuous
need for this information during time intervals which do not correspond to the routine meteorological evaluation periods. The location of the CERN station is indicated in Fig. 1.

From the synoptic data the mean annual wind directions and forces in this region have been calculated and can be seen from Table 1. The mean annual wind velocity is 10.6 km/h. At all seasons the prevailing winds are NE or SW.

The mean annual precipitation averaged over 136 years (1826 - 1961) is 860 mm. The seasonal distribution of precipitation calculated over the same period is 19% in winter, 22% in spring, 29% in summer, and 30% in fall.

**Temperature:** Recorded continually about 1 m above ground on bimetallic thermograph with a temperature span between -35°C and +45°C, ±1.5% deviation of total, daily or weekly time scale.

**Air pressure:** Read on station barometer, span 790-630 mm mercury, deviation within ±0.2 mm. Thermometer is attached. Readings are corrected for temperature and gravity.

**Humidity:** Recorded continually about 1 m above ground with hair hygrograph, span 5-100% relative humidity, ±2.5% deviation, daily or weekly scale. The response is temperature dependent. At room temperature 90% of a sudden humidity change shows up within 3 min. With decreasing temperature the lag is slightly longer. The instrument is sensitive to dust. This might lead to errors up to 15%. These are reduced by washing the hairs from time to time with a soft brush.

**Precipitation:** The components moisture, rain and snow are continually recorded on a weekly scale. The quantity of moisture deposited on a hair grid of 100 cm² surface is measured with a Hiltner dew balance. The instrument is installed wind sheltered about 30 cm above ground. The measured quantity is composed of dew fall, distillation dew, and fog. The deviation lies within ±0.1 g. The quantity
of rain and snow deposited on the site is determined from measurements with a rain gauge of the Hellmann type. The collector is a funnel of 200 cm² receiving area. Automatic electric heating at temperatures of 4°C or lower allows the measurement of the water equivalent of snow falls and avoids freezing of collected precipitation.

The meteorological data are evaluated in periods corresponding to the sampling periods of air and water.

**Sampling, radioactivity counting**

Environmental radioactivity is controlled over a Laboratory site of 80 hectares, about 8 km northwest of Geneva on the Franco-Swiss border. About half of this terrain is situated in a shallow depression. On this site are located two high energy proton accelerators, a 600 MeV synchro-cyclotron and a 28 GeV synchrotron with intersecting proton storage ring. During the past years until 1970 the intensity of the synchro-cyclotron increased from 0.3 to 1.5 µA, of the synchrotron from $2 \times 10^{10}$ to $1.4 \times 10^{12}$ particles/burst (1 burst per 3 sec). For 1971 a tenfold intensity increase was projected.

Accelerator produced radioactivity is surveyed at strategic and representative points on the site. The equipment consists of automatic air and water monitors and of sampling devices without radioactivity counting facilities, this latter because most locations on the Laboratory site are relatively strongly influenced by the locally and in time varying stray radiation from the accelerators which gives rise to uncontrollable counter background variations and to irreproducible measurements.

The samples are periodically collected, prepared and counted for radioactivity in a shielded low-level laboratory of the Health Physics building.

Table 2 lists the monitored subjects together with the sampling frequencies, the time after collection at which radioactivity is measured, and the sampling locations on the site. These locations can be seen from Fig. 1.
The extent of environmental radioactive pollution from the accelerator operation is determined from total beta and gamma activity measurements, and from beta and gamma-ray analyses. This is because activation of the materials in the radiation areas through spallation, \((\gamma, n)\) reactions and thermal neutron capture leads to both beta and gamma emitters. Tables of the expected isotopes based upon theoretical considerations have been published with the isotope production reactions and decay modes\(^5,6\). Alpha activity controls of environmental samples have so far shown no isotopes of accelerator origin.

**Airborne radioactivity monitoring**

Airborne radioactivity monitoring is based upon the collection of particulate matter suspended in ground-level air. A measurable volume of air is passed through a suitably efficient filter material.

**Air monitoring equipment**

Eight movable samplers and one fixed installed automatic monitor are operated.

The movable samplers consist of suction devices with fixed filter discs of 5 cm diameter. The motors operate at 230 V, 1.5 A, with a noise level of about 55 dB. Overheating in case of filter clogging is avoided by an additional air intake through a by-pass. The volume of sampled air is determined from the integrated air-way indicated on the built-in anemometer. The average flow rate without filter differs between the old and the new model from about 25 to 40 m\(^3\)/h. Depending on the type of filter material used the air-flow rate drops to about 10-25%.

The sampling duration depends on the specific conditions of the location and on the type of study carried out. Environmental air is sampled mostly over 24 hours or 72 hours during weekends. For continual sampling over these periods the lack of an overflow indication for the anemometer readings is a disadvantage. It was overcome by laboratory tests of each sampler under varying conditions\(^7\).
For sampling from badly accessible areas a flexible tube is put between filter holder and anemometer. This makes a correction necessary for the calibration factor of the anemometer\(^7\).

Maintenance is provided in the CERN workshops. Every 300-500 hours of operation the motor brushes are renewed and the inner parts of the samplers cleaned. The gaskets are periodically renewed. The rubber gasket in contact with the filter is slightly talcum powdered or a teflon ring laid in when the filter material is sticky. For low air-resistance filter material the sampler input voltage is transformed down to increase brush lives.

For field operation the samplers are sheltered. They are located away from busy roads and parking areas, and operated about 1 m above ground, to minimize uptake of car exhaust pollutants and of dust deposited on the ground. The orifice plane is kept vertical. Temperature and humidity are recorded. The influence of meteorological parameters on air sampling has been reported\(^8\). The sampling points can be seen from Fig. 1. The construction of the intersecting proton storage rings, booster and other buildings prevented regular sampling over the western part of the Laboratory site at the time.

The automatic air monitor is sheltered in a hut. It has sampling and counting facilities. The outdoor air is sampled through a pipe at a mean rate of 12 m\(^3\)/h -- anemometer indicated -- through a continuously moving filter tape. The tape speed can be varied in steps of 1, 4 and 16 mm/h. The speed of 4 mm/h is used.

The dust loaded filter tape passes underneath two GM counters for total beta activity measurements immediately after sampling and with a delay. The delay time between first and second measurement can be varied by changing the moving speed of the filter tape and the distance of the second to the first counter. The delay time used is 100 hours which allows discrimination against natural radioactivity from Radon and Thoron daughters. The mean counter background is 18 cpm, the efficiency 30% for energies above 1 MeV.

The data of the counters are continually recorded by a multicolour point recorder and a wax-tape printer. The filter tape is
cut into weekly strips which are gamma-ray analysed in the laboratory. All data are computer processed.

The control point, representative for the Laboratory site, is indicated in Fig. 1. It is situated on the roof of the Health Physics building. It has been selected after studies of wind and air activity distribution on the Laboratory site and after measurements of stray radiation, this latter to make sure that the counter background of the air monitor is relatively low and stable.

**Filter material**

Theory and practice of aerosol filtration have been reported by various authors\textsuperscript{9-11}.

Three different types of filter material are used in the control of radioactive air pollution near the CERN high energy accelerators: Firestone paper filters, Delbag Microsorban 99/97, and glass fiber filters.

Advantages of Firestone paper filters are relatively low air resistance, good mechanical strength, ease of handling, low cost. They are, however, strongly affected by moisture and have low collection efficiency for particle sizes below about 1 \( \mu \)m. The efficiency for particle sizes of between 0.2 and 0.004 \( \mu \)m is less than 10%\textsuperscript{12}.

This filter material is used for routine air sampling with the movable equipment in hot areas after accelerator shut-down. It was also used in the first field studies.

Microsorban filters composed of *polystyrene* fibers have the advantage of a high collection efficiency over a wide particle size range. For particles below 0.3 \( \mu \)m the filters are about 100% efficient\textsuperscript{13}. Further advantages are that the filters dissolve easily in benzol without residue, can be shrunk on a hot metal plate to any smaller diameter, or ashed. Residue-free dissolution of the filter enables grain studies through sedimentation analyses, and particle size spectrum analyses. Shrinking is done when necessary to accommodate counter trays. On the average this gives 20% less activity loss than the normally used method of ashing the filter.
At room temperature the influence of air moisture on the filter material was found significant above 60% r.h.\(^7\). Disadvantages of Microsorban filters are: relatively high air resistance, low mechanical strength, stickiness, high cost. Because of aerosol penetration into the upper fiber layers of the filter, alpha particles are partly absorbed. Direct alpha measurements therefore have to be corrected accordingly. For practical purposes a factor of 2 is applied\(^{14}\).

Microsorban filters are used with the movable samplers for investigations of radioactivity distribution and concentration for particle size studies, and for assessment of the inhalation risk inside the high energy accelerator installations and in the environment.

The fixed installed air monitor is supplied by the manufacturer with a specially developed glass fiber filter tape. The material is highly efficient, has relatively low air resistance, good mechanical strength, is easy to handle and slightly more influenced by humidity than the Microsorban filters.

The various filter materials are stored in clean, dry containers. To compare filter weights before and after sampling the filters are dried at moderate temperature for some time in a furnace.

Radioactivity of the filter discs is measured in the laboratory.

**Monitoring of precipitation activity**

The precipitation collector is an inox funnel, 1 m\(^2\) catchment area, recently installed on the roof of the automatic air monitor hut. The water is drained through a tube into the hut and received in a container, connected by an overflow tube with a second container. Heating under the funnel is foreseen to melt snow and prevent sample freezing.

This collector replaces the former plastic tray sampler of 0.4 m\(^2\) surface. A plastic bottle screwed on under a hole in the tray middle tilted the collecting surface slightly down by its weight and provided drainage. Heating was installed under the tray. The sampler
worked continuously from December 1968 to May 1969. It was replaced because of plastic aging under the field conditions.

Advantages of the plastic tray sampler are, besides the low cost: low wall absorption of the material, ease of handling and cleaning, low heat absorption and sample evaporation.

Absorption of radioactive substances can be further reduced by filling the sampling system for some time with multiple carrier solution. During dry weather dust deposited on the tray was collected to study its radioactivity and to avoid contribution to precipitation activity. Tray cleaning was done with the acid used for further sample preparation.

Disadvantages of this tray sampler were: small collection surface, material aging. These disadvantages are eliminated using the inox funnel. However, the advantages mentioned above for the tray sampler are lost. Therefore, tray samplers from weather resistant, polystyrene fiber hardened plastic material, 1 m² catchment area, 20 cm wall height are recommended.

The samples are periodically collected, brought to the laboratory, weighed, the pH value measured, acidified to a pH of about 3, evaporated to dryness, the residue transferred into counting planchets, and the radioactivity measured.

This procedure is easy and less specific for the preparation of the isotope mixture than others. Volatile substances are lost. The mean systematic error from sample preparation by this method is about 20%\(^1\).\(^5\)

Gamma-ray analyses can be carried out directly on the water samples.

Monitoring of drainage water activity

The CERN drainage water leaves the Laboratory site at three different points indicated in Fig. 1. The drains collect rain- and cooling water from the electrical installations outside the accelerators, operating water, and to some extent ground and spring water.
The main effluent (1) with a flow rate between 150 and 2000 l/min drains the southern part of the Swiss and the French terrain. Effluents (2) and (3) with flow rates between 100 and 800 l/min drain the northern parts of the Swiss and the French terrain.

The effluents leaving the Laboratory site are controlled by automatic water monitors, sheltered in huts. The monitors have sampling and counting facilities.

The water is pumped up from the sewer pipe into the hut and applied with a small pump at a feed rate of 240 cm$^3$/h to a continuously moving filter-paper tape. The tape speed is 3 cm/h. A motor driven tube distributes the water dropwise over a given surface on the tape. Infrared heating under this part of the tape provides the evaporation heat. As the tape moves on it passes a scintillation counter for total beta activity measurements which are printed out. The counter efficiency above 1 MeV is 30%. The tape is cut into weekly strips which are gamma-ray analysed. All data are computer processed.

The water monitors manufactured by the same company as the air monitor do not fulfil the demands of continuous monitoring as satisfactorily as does the air monitor. For this reason a study of the technical problems associated with this equipment has been carried out both to increase the reliability and the precision in the measurements.

The small pump of the monitor blocks easily with incoming particles suspended in the water. The electric circuitry of the pump is insufficiently protected against condensing water. This leads to frequent short circuits. When the tape is moistened its mechanical strength decreases, and the pulling force of the transport mechanism can tear the paper. It also does not always keep the intended position over the heating and burns.

To avoid these difficulties several modifications have been applied to the monitors. Further, the counter background was reduced from 250 cpm to 110 cpm by lead shielding. Background variations can be controlled on neighbouring radiation monitoring instruments.
A new water monitoring system with field sampling, laboratory counting and direct gamma activity controls is under study.

**Monitoring of sludge activity**

Sludge accumulating in drainage cleaning shafts is periodically sampled. Intermittent sampling is carried out from the sewer near water monitor 1, and from the streams receiving the effluents.

The samples are gamma-ray measured, dried at about 100°C to constant weight, washed out with distilled water, and filtered. The filtrate is evaporated to dryness, transferred into planchets and beta activity counted.

**Monitoring of soil activity**

Excavator sampled soil from between 1 and 2 m below surface of the proton synchrotron earth shielding has been controlled after a year of continuous accelerator operation. Chemical treatment of the samples, liquid scintillation counting and results have been reported.

**Laboratory counting of radioactivity**

A low-level, temperature stabilized laboratory in a cellar of the Health Physics building is equipped for total radioactivity measurements and isotope analyses.

For total beta activity measurements a low-level GM counter and an anti-coincidence methane flow counter are used. The GM counter is manually operated; for 1" planchet size the mean background value is 1.7 cpm. The flow counter has an automatic sample changer for up to 100 samples; for 2" planchet size the mean background value is 2 cpm. The flow counter is also used for total alpha activity measurements.

The counters are K-40 and Rb-87 calibrated. The calibration samples are prepared from dry, ground KCl and RbNO₃ powder, sprinkled smoothly on the planchets, fixed with a few drops of alcohol and acetone respectively, and dried under an infrared lamp. Figure 2 shows the calibration curves in function of the sample weight for the energies 1.35 and 0.275 MeV. For the flow counter stainless
steel planchets are used, for the GM counter plastic planchets. Extrapolation of the calibration curves to zero thickness shows the counting efficiency to be about five times lower for the lower energy. The gamma response of the counters, Be-7 measured, is about 0.1% for the GM counter and about 0.2% for the flow counter.

The reported radioactivity data are obtained with the K-40 calibration, or, in case of the automatic air and water monitors with Sr-90/Y-90 calibration to facilitate comparison with data from other environmental monitoring laboratories. The Sr-Y-90 calibration curve lies between that of K-40 and of Rb-87, rather close to that of K-40.

Gamma-ray measurements are carried out on a 3 x 5" NaI(Tl) and on a 44 cm$^3$ Ge(Li) detector. Four hundred and 8000 channel analysers are used. The latter has simultaneous counting facilities for up to eight detectors. The spectra can be displayed, plotted, printed, punched on tape, and are computer processed. Direct data transmission computer on line is foreseen with the CERN Focus system.

The 3 x 5" NaI(Tl) detector has a mean background, integrated up to 2 MeV, of 400 cpm. The resolution is 3.8% at 0.66 MeV. The Ge(Li) detector is co-axial, 40 mm outer diameter, 8 mm inner diameter of sensitive surface, 37 mm height. The resolution is 2.4 keV at 0.66 MeV. Peak to Compton ratio is 20:1. Total detector efficiency for sample position at cap is 4.7% at 0.47 MeV.

Alpha-ray analyses are carried out with a silicon diode of 33 cm sensitive diameter. The resolution is 90 keV at 5.15 MeV, the efficiency 40%.

To fulfil the objectives of radioactivity monitoring listed before, maximum accuracy must be achieved when radioactivity levels are close to safety norms. These are defined in the CERN Radiation Safety Manual and correspond in general to the ICRP recommendations. The levels so far measured in the environment of CERN and due to the accelerator operation are well below tolerance levels except for soil samples from target areas of the synchrotron earth shielding. Radioactivity values well below tolerance are reported
here without indication of error limits. The systematic errors
during sample collection, storage, and preparation are kept as low
and as constant as possible. To obtain statistically reliable
results the radioactivity counting times are optimized\textsuperscript{19}.

Monthly reports on the data of continual air and water radio-
activity monitoring are issued.

3. **MEASUREMENTS**

Measurements of environmental radioactivity at CERN reveal three
components: natural radioactivity from soil sources and from cosmic
ray created spallation products, fission products from nuclear bomb
tests, and induced radioactivity from accelerator operation.

The purpose of the measurements is to determine the degree of
contribution of induced radioactivity from operating the CERN high
energy installations to the total environmental levels, and to en-
sure that it remains within acceptable limits. To this end the
spatial and temporal radioactivity distribution is studied in rela-
tion to the various accelerator operating conditions, and isotope
analyses are carried out.

Discrimination of induced radioactivity from natural and
fission product activity is done through isotope analyses and data
comparison with neighbouring radioactivity monitoring laboratories.
Airborne radioactivity measurements are taken at 100 and 150 hours
respectively after the end of collection to keep the contribution
of natural Rn and Tn daughters small.

**Airborne radioactivity measurements**

Induced airborne radioactivity originates from nuclear inter-
action between high energy radiation and the various air constituents:
nitrogen, oxygen, argon, carbon dioxide, water vapour, pollutants,
and aerosols. The main isotopes that can be created from air activi-
tation are:

\[\text{O-15 (2 sec), O-14 (74 sec), N-17 (4 sec), N-16 (7 sec),}\
\text{N-13 (10 min), C-14 (5600 y), C-15 (2 sec), C-10 (19 sec),}\
\text{C-11 (20 min), A-41 (1.8 h), A-37 (35 d), Be-10 (2.7x10^6 y),}\
\text{Be-7 (54 d), H-3 (12 y), P-32 (14 d), P-33 (24 d), S-35 (87 d).}\]
The basic nucleogenic substances are to be expected in gaseous phase. A fraction converts into particulates. This occurs partly through gas absorption in aerosols and in dust, partly through direct materialization by radiolytic and photolytic reactions stimulated by magnetic fields and the influence of the high energy radiation. The role of such reactions in the presence of ionizing, natural radiation has been shown in experiments with free atmospheric air. The particulates grow through hydration and coagulation and can be collected on filters.

**Measurements at the CERN proton synchrotron**

The 28 GeV proton synchrotron (PS) is located in an underground ring tunnel building of a diameter of 200 m. The proton injector is a 50 MeV linac. Four experimental halls are attached to the ring tunnel from which they are separated by concrete shielding blocks.

The ring tunnel is air conditioned to provide temperature and humidity stabilization and is kept on a slight air overpressure of a few millimeters of water to prevent atmospheric dust from entering. Air conditioning implies a closed ventilation circuit by blowing air through pipes with holes at the floor under the accelerator and by sucking it in at the ceiling above. Overpressure is maintained by air intake through eight ventilation stations, where the air is cleaned, temperature and humidity conditioned. The total intake rate is 40,000 m³/h, which corresponds to about three complete air changes per hour in the ring tunnel. This air escapes through numerous openings of the ring tunnel into the experimental halls and into the open. These openings are untight doors and shieldings, grid doors, tube-, cable-, beam-holes, etc. No main release points exist.

The average air loss through different types of openings was measured and amounted to one third of the total. Through slits in an untight door of ordinary size about 30–60 m³/h of air is lost. A door with a grid of 0.3 m² in its upper part has a total air loss of about 1100 m³/h.

During normal accelerator operation the ring tunnel is not accessible. Measurements of airborne radioactivity were carried out
during linac injector tests, when certain parts of the ring tunnel were accessible. Measurements with a gas monitor showed activity values of up to 6.7 mCi/m$^3$ in the target zone and lower than 2 µCi/m$^3$ in ring sectors. Decay of the radioactivity was followed up to 100 min after sampling. At that time 2% of the initial radioactivity value was measured. The isotopes identified from decay curve analysis were O-15, N-13, C-11, and A-41$^{21}$.

Radioactivity measurements of the particulate component of air in the target area of slow ejection show total beta activity of 40 nCi/m$^3$ seventeen minutes after the end of operation on the target. After 100 minutes the value drops to about one tenth$^{22}$.

Systematic measurements of the long-lived particulate component escaping from the ring tunnel at points of heavy air loss have been made during periods of normal operation, excluding testing and shut-downs of the accelerator. The sampling points indicated in Fig. 3 were equipped with air sampler, hydrogen-filled ionization chamber for continual recording of neutron and gamma radiation, thermograph and hygrograph. Filter exposure times were varied according to accelerator operation conditions between 1 and 72 hours. Two hundred and forty-five exposures were made between December 1969 and October 1970. After exposure the filters were measured for total $\alpha$ and $\beta$ activities, and $\gamma$-ray analysed. Radioactive decay was followed up between 1 and about 1200 hours after end of filter exposure. Radioactivity levels were compared with radiation recordings. The correlation is significant. The correlation factor is 0.94 at 98% confidence limit. Alpha radioactivity was of natural origin at all sampling points. Total $\beta$ and individual isotope activities varied with the different accelerator operation modes. The highest activities were measured close to targets and ejection areas. For normal accelerator operation, excluding periods of testing and of shut-downs, the mean value of total $\beta$ activity averaged for all sampling stations over the entire period under investigation was 300 pCi/m$^3$, one hour after sampling of an average duration of 24 hours. About 2% of this value was found 150 hours after end of sampling, and about 0.5% after 1000 hours. The figures are obtained by fitting the measurements...
with the best curve by the least square method. This curve has the shape of a decay curve, but not its physical meaning.

Individual decay curve analyses for each exposure, as well as β-ray analyses of samples show that the long-lived radioisotope mixture of the particulate component of the air is composed mainly of the pure β emitters P-32, P-33 and S-35. Gamma-ray analyses show Be-7. Figure 4 gives an example of spectra from samples collected during normal accelerator operation and after shut-down.

From the quantitative Be-7 measurements of the samples collected at the various locations around the accelerator building during normal machine operation a mean value of 60 pCi/m³ results for the entire period of investigation. The mean contribution of Be-7 to total particulate activity 1 hour after end of 24-hour sampling is about 17%. At that time P-32 contributes less than 10%, P-33 and S-35 less than 5%. Results obtained from individual samples may show deviations from the above quoted percentages. They remained within a factor of five for the investigated locations.

Figure 5 shows the local distribution of long-lived radioactivity of the particulates in air and of their concentration during normal accelerator operation. The values are the means for the entire period and refer to the above given mean sampling duration. Total β activity is given 150 hours after the end of sampling. The figure shows similar trends for the total β and Be-7 activity curves. The activity peak of both curves lies at location 4 (Fig. 3). This is the closest sampling point to targets and ejected beam areas. Location 1 (Fig. 3) shows the low activity and the low concentration of particulates in air. The high concentration measured at location 2 was confirmed by air samples taken from the tunnel opposite this point at location 8.

The mean concentration of particulates in the accelerator air averaged for the various locations and for the entire period is 60 µg/m³ during normal accelerator operation. This is one third of the average concentration of particulates in air at the Laboratory site23). During shut-downs the concentration of particulates in accelerator air increased at all locations by 40% and more. Long-
lived total $\beta$ activity, 150 hours after end of sampling, dropped during shut-downs to about 5% of the value for normal operation. From total $\beta$ activity decay analyses Ca-45 was detected in samples taken during accelerator shut-downs. This indicates uptake of dust deposited inside the accelerator building through air turbulence. Ca-45 mainly originates from activated concrete dust. Isotopes from activated metallic dust from the accelerator were not detected. Their residence time in the air of the accelerator building is short.

During construction of the intersecting proton storage rings the future beam extraction hole through the shieldings into the accelerator ring tunnel was open and accessible. Air from the accelerator building sampled at this location during operation of the proton synchrotron shows a relatively low mean of total beta activity of 2 pCi/m$^3$ 150 hours after sampling. Be-7 activity ranges between 30 and 120 pCi/m$^3$. The ratio of total beta to Be-7 activity 150 hours after sampling was fairly constant, 0.03.

The ratio between total beta activity of the particulates suspended in air and total airborne radioactivity was found to be $1:3 \times 10^3$ for the CERN proton synchrotron 1 hour after short-term sampling$^{22}$. Applying this ratio to assess the mean level of total airborne radioactivity released from the accelerator building during normal operation for the period under investigation, a value of 1.1 µCi/m$^3$ is obtained from the quoted figures 1 hour after sampling. The mean Be-7 contribution at that time is 0.05%. This explains why it was found impossible to detect Be-7 by gas monitoring$^{21}$. Similarly, the contribution of H-3 induced in dry air would be far too small to detect this isotope by the above method.

Samples of atmospheric water vapour collected at location 4 (Fig. 3) close to targets and ejected beams, show a mean tritium activity of about 700 pCi/m$^3$ of air. The water vapour was frozen out from the air escaping at this point from the ring tunnel, and the samples were counted with a liquid scintillation counter.
Considering that the air volume escaping per hour from the proton synchrotron building is about 40,000 m³, the mean value of total airborne radioactivity discharged during accelerator operation into the environment is about 44 mCi/h for the investigated period, 1 hour after 24 hours sampling; about 2.4 µCi/m³ is due to Be-7 activity.

Air released from the ventilated 50 MeV linear injector accelerator building was sampled over 24 hours. Radioactivity measurements 1 hour after sampling show a mean total β activity of 100 pCi/m³, decaying to 0.5 pCi/m³ after 150 hours.

Airborne radioactivity levels comparable to those of the synchrotron building were detected during beam ejection in the experimental halls. The halls are unventilated; however, air exchange with the open is rapid. After stop of the ejected beam the long-lived total beta activity of particulates in air on 24-hour samples dropped to below 1 pCi/m³ after 150 hours. The isotopes identified from the mixture are the same as in the air of the accelerator building. Ca-45 was found in samples taken during operation and during stop of the ejected or the accelerated beam and indicates the presence of dust from the cement in the air of the halls.

Airborne radioactivity discharged from the CERN synchro-cyclotron

The air from the 600 MeV synchro-cyclotron is released at the roof of the accelerator building. During accelerator operation this location is not accessible. To assess the levels of airborne radioactivity released into the environment measurements were carried out at the ventilation shafts of the accelerator building when this area was still accessible¹⁴), and inside the accelerator hall⁶).

Measurements of airborne radioactivity at the Laboratory site

Continuous measurements of long-lived total beta and gamma activity of particulates in ground level air of the Laboratory site have been carried out since August 1969. The data are used to assess total airborne radioactivity originating from operating the Laboratory, deposition of radioactive particulates from air on the site, and to
ensure that accumulation of radioactive particulates deposited in the environment does not give rise to long-lived radioactive contamination.

The monitoring practice adopted at CERN allows data comparison with the network of fallout radioactivity monitoring laboratories within the required accuracy. Figure 6 shows good agreement and the same trends of the total radioactivity levels for the data of CERN and for those of other Laboratories. The characteristic seasonal variation of fallout radioactivity from nuclear bomb tests with its winter minimum and spring maximum is observed. The CERN data gives no noticeable indication of an additional radioactivity source located about 300 m from the monitoring station. Within this distance prevailing radioactivity patterns are found showing the influence of accelerator operation. In several cases daily monitoring data show that the start of accelerator operation coincides with a peak of environmental air activity. For accelerator shut-downs no significant total beta activity changes are observed. The contribution of total beta activity of aerosols originating from operating the proton synchrotron at present intensity and energy was assessed not to exceed a mean of 0.3 pCi/m$^3$.

An environmental activity of about 0.5 pCi/m$^3$ is obtained from Be-7 monitoring during accelerator operation after subtraction of the natural contribution. During periods of accelerator shut-downs the Be-7 activity drops rapidly to natural levels.

The environmental concentrations of accelerator produced P-32, P-33, S-35 and Ca-45 in air are extremely small.

Radioactivity of particulate matter

To assess the extent to which high energy radiation might activate particulate matter in air, dust loaded filters from 24 hours air sampling on the Laboratory site were stored until their radioactivity had decayed to about background counting rate and then combined with a duplicate set of blank filters. These filter sets were irradiated for about 24-72 hours in the synchro-cyclotron beam. Three hours after irradiation surface doses of several hundred millirads were
measured. Total β activity and γ-ray spectra were recorded and the radioactive decay followed. Both dust-loaded and blank filters showed identical isotopic composition, indicating that their induced radioactivity originated from activation of the filter material rather than from activation of the dust load on the filters.

Isotope analyses of dust collected from electromagnetic units inside accelerator buildings and experimental halls show Mn-54, Fe-59, Na-22, Co-60, Se-46 and Ca-45 from activation of concrete shielding or machine parts. With the exception of Ca-45 none of the above isotopes could be detected in any of the air samples.

Dust-fall collections at the Laboratory site about 300 m from the nuclear installations show no accelerator produced isotopes other than Be-7.

Radioactivity measurements of precipitation

Radioactivity measurements of precipitation serve to determine the wash-out of accelerator produced radioisotopes from air and soil. In 1970 precipitation made on the average the highest contribution to total drainage effluent water.

In Fig. 7 monthly means of specific total β activity of precipitation are given for CERN and for other Laboratories from December 1968 to May 1969. The monitoring techniques at the quoted stations allow data comparison within the accuracy required. Good agreement of trends and levels is noticed. At all stations the spring radioactivity maximum is present. It is typical for the seasonal variation of fission product activity from nuclear weapons tests. Total β activity measurements of CERN precipitation show no evidence for wash-out of accelerator produced radioisotopes.

The influence of local pollution becomes small for most air constituents in large rainfalls. Be-7 analyses of rainfalls below 2 mm sampled 300 m from the accelerators and directly γ-ray spectrometered show concentrations mostly comparable to natural.

The wash-out efficiency of snow flakes for particulates suspended in air is on the average about 20% higher than that of rain droplets. Radioactivity of fresh snow sampled from 1 m² areas,
3-5 cm layer-depth, was controlled. The sampling locations were on the Laboratory site, outside the site up to 5 km downwind, and on the French Jura, a mountain chain of about 1700 m a.s.l., 12 km north-west of the Laboratory. There any influence of radioactivity from the CERN installations is excluded.

Total $\beta$ activity of the snow samples varies locally. No systematic variation with distance from the Laboratory could be observed. The range of the radioactivity variations lies within that of Jura reference samples. Gamma-ray analyses reveal natural emitters. Figure 8 shows an example of a snow sample spectrum. The sampling location was about 200 m from the synchro-cyclotron.

pH values of precipitation from within and around the Laboratory are on the average lower than those of Jura reference samples. This might reflect the influence due to industrial pollution in the Geneva area.

During the above precipitation control period from December 1968 to May 1969 only several weeks periods of continuous air radioactivity measurements are available at CERN. The wash-out ratio, defined as the ratio between mean specific $\beta$ activity of precipitation and of air, lies for these periods within the range of values obtained at other Laboratories.

Attempts were started to assess the role of condensation in the removal of airborne, accelerator produced isotopes in the immediate neighbourhood of the accelerator installations and inside experimental halls. This work indicated that more effort should be made in this direction.

Radioactivity measurements of CERN drainage water effluents

Continuous radioactivity monitoring on the main effluent 1 started in August 1969, on effluent 2 in August 1970, and is being prepared for effluent 3.

The results of radioactivity monitoring of the main effluent 1 (Fig. 1) are plotted in Fig. 9 together with the monthly amounts of precipitation deposited on the Laboratory site drained by effluent 1. Coincidence between small amounts of precipitation and
high values of specific drainage water radioactivity are noticed. This indicates wash-out of radioactive dust deposited on the laboratory site and of accelerator produced radioactive soil constituents. The low level of drainage water radioactivity reflects the soil retention of radioactive products, which is generally high, and isotope dilution in drainage waters carrying no accelerator produced radioactivity.

The amount of radioactive soil constituents dissolved by infiltration of precipitation depends on soil and water quality, chemical properties of the activated soil constituents and on the rate of water movement through the soil. Daily measurements of drainage water radioactivity and of precipitation show that when precipitation penetrates slowly into the soil layers, retention of radioactive products by the soil is high. This agrees with concentration measurements of individual isotopes produced by high energy radiation penetrating into the earth shielding of the proton synchrotron. Equilibrium distribution coefficients between water and soil of $10^{-2}$ for Na-22 and $10^{-3}$ for Ca-45 have been measured. They were estimated to be of the order of $10^{-2}$ for P-32, Mn-54, Be-7.

Short and heavy rainfalls during which no equilibrium between ions in solid and in liquid phase is reached are related to sudden peaks of drainage water radioactivity and of sediment concentration in the water. This situation was found in November 1969 and explains the relatively high amount of precipitation coinciding with a peak of effluent water radioactivity.

Figure 10 compares the trend of the monthly total $\beta$ activity discharged by the main effluent with that of precipitation (data from Mol, Belgium) and of accelerator intensities. As precipitation penetrates the ground, the seasonal amplitudes of radioactivity variations are quenched and no longer detectable after dilution in the drainpipes with waters carrying less or no accelerator isotopes. From these data the influence of accelerator operation on effluent water radioactivity cannot be excluded. The high amplitude of the drainage water radioactivity peak in November 1969 reflects the peak in accelerator intensity as well as strong wash-out of radioactive soil constituents by heavy rainfalls during this month.
To check efficiency and results of the water monitors sampling was carried out at four extra locations during several weeks. Three of them were under the manhole: at the entrance pipe of the main effluent 1 (see Fig. 1) into the sewer basin, at the turbulent area under the pipe entrance, and at the quiet water zone on the sides. The fourth was in a parallel location to the monitor from the container built on to the pipe carrying effluent water into the monitoring hut. Further samples were taken from the Satigny rivulet about 100 m downstream from the entrance of effluent 2, and about the same distance downstream from the entrance of effluent 1. The samples were treated as described for precipitation samples, β counted and γ-ray analysed. Gamma-ray analysis of untreated samples was also done.

Daily variations of effluent water radioactivity from sampling in parallel with the monitors agree with those obtained from the monitors. Significant local differences of total β activity were found for the samples taken at the manhole. The lowest activity values were obtained from the pipe sample. The sample from the turbulent area showed about double this value. The highest value, about three times that of the pipe sample, was found for the quiet water zone. The sediment concentration of the water was the same (0.3 g/l) at all three locations.

Be-7 was found to be a good indicator for the presence of accelerator produced radioactivity and is γ-spectroscopically easily detectable. For this purpose the sample should be untreated, since Be-7 is lost to a great extent during evaporation. This was found to be a further disadvantage of the water monitors; however, it does not affect the total β activity results. The γ-spectroscopical Be-7 concentration measurements on the weekly monitor tape samples are too low. They will either have to be corrected for the evaporation loss of Be-7, which is difficult to do, or different methods must be applied for Be-7 monitoring of effluent water. A similar problem arises in the presence of Na-22 in the effluent water. Controls could be carried out on untreated effluent water. Direct measurements with a γ detector in or above effluent water might be considered.
The small pump applying effluent water dropwise onto the monitor tape is supplied from the above mentioned container built onto the pipe which carries the effluent water into the monitor hut. Particulates suspended in effluent water settle down in this container, algae grow at the side-walls. The container is emptied and cleaned every two to three weeks. Isotopes attached to the bottom sediment of the container or incorporated by algae are lost from monitoring. Radioactivity controls of the container content compared with those of effluent water from the sewer pipe and with the monitor data have not yet cleared up to what extent this effect must be taken into account. The factor by which the monitor readings could be too low might be of the order of 2 for monthly radioactivity means. Because all readings were well below permissible this order of magnitude could so far still be tolerated.

A further disadvantage of the water monitors is that they cannot provide information on the tritium levels of effluent water. The reason is not the low counter sensitivity for soft β radiation, but the complete loss of tritium in the evaporation process. The need for tritium controls of effluent water was discussed recently when samples of atmospheric water vapour, soil moisture and water in contact with hot areas showed a significant tritium content. Due to dilution with tritium-free drainage waters low effluent concentrations are expected.

The problem of underestimation of total effluent radioactivity due to the presence of soft β-emitting isotopes, Ca-45 etc., was studied. It is felt that counter calibration with Rb-87 accounts better for this situation.

Radioactivity measurements of sludge samples

The sediment trapping shafts on the drain pipes are routine-emptied at intervals of several weeks to several months. Radioactivity analyses of the sediments accumulated over these periods show a defined isotope and radioactivity distribution pattern over the Laboratory site. Close to the accelerators high radioactivity levels are found. Co-57, Co-58, Co-60, Fe-59, Mn-54 and Sc-46 were detected. When drying sludge samples Be-7 was found to be easily lost. Gamma spectroscopy has therefore been carried out before sample treatment.
Cs-137 found in the samples originates from nuclear bomb test fallout. The results indicate correlation between Cs-137 content and duration of sludge accumulation in the sewer.

Sediment was sampled from bottom and sides of the sewer basin of the main drain and from the rivulet of Satigny up to 100 m downstream of the entrance of effluent 1 and of effluent 2 (see Fig. 1). There is no indication of the presence of any accelerator produced isotopes mentioned above other than Be-7.

4. DISCUSSION AND CONCLUSIONS

The results of environmental radioactivity monitoring at CERN demonstrate that high energy nuclear Laboratories are large-area sources of induced radioactivity. Irradiation takes place at all locations where high energy primary, secondary or stray radiation passes. Induced radioactivity depends on quality, quantity and duration of radiation incident to different materials, on the type of nuclear reaction with it, geometrical factors, the material itself, and the time after exposure. Irradiated materials whose radioactivity adds to environmental radioactivity were found to be soil, water, air, particulate matter, dust. Most of the induced isotopes detected in those materials are spallation or neutron activated products whose irradiation can be traced back to have occurred in the area of accelerators, experimental buildings and their immediate neighbourhood. Outside this area the probability of inducing detectable amounts of radioisotopes is negligible. Stray radiation intensity rapidly drops off with distance. About 100 m away, stray radiation adds less than a level equal to natural environmental radiation. It is composed mostly of neutrons. In defined directions muon radiation is selectively observed.

The induced radioactivity source was found to be of very complex structure with hot spots, a wide intensity and energy spectrum varying locally and in time according to different beam layouts and the operating modes of the high energy particle beams. The source area has no main release points, radioisotopes spread diffusively. A large number of induced radioisotopes are found in the environment of the high energy accelerator installations.
Half-life studies of induced radioactivity released from the source area show short-lived components with half-lives between seconds and minutes and long-lived with half-lives between days and years. The number of isotopes with half-lives of hours is small, the most important representative being A-41. Many of the radioisotopes produced from environmentally important elements such as H, C, N, O, S, Si, Mg, Ca, etc., are short-lived, like most of the radioactive gases produced from air.

Under present operating conditions of the CERN Laboratory no hazard compared to the present acceptable levels is to be expected for the CERN Laboratory site and for the public environment from either short or long-lived radioactivity. Radioactivity from nuclear installations can become important where high concentrations of radioactive materials are released with high travelling speed into a defined direction or if radioactive material accumulates at preferred locations, in materials or tissue, thus building up high concentrations there.

The radioactivity controls at CERN show that no such conditions have occurred or could be expected to occur under present operation. Radioisotope concentrations leaving the Laboratory site are low. They are significantly lower than those released from the source area. The latter are below permissible concentrations although at hot locations they can be close to or slightly above.

Concentrations remain low, because compared to the total area the dimensions of hot locations are small, and besides geometrical dilution, further dilution occurs through continual supply of fresh air and water. Moreover, on environmental pathways, a number of processes like radioactive decay, diffusion, absorption, fractionation, molecular and ionic exchange, incorporation of radioisotopes into soil or biological organisms, etc., decrease concentrations of the Laboratory releases. Although within a radius of about 300 m from the source area prevailing patterns of induced airborne radioactivity could be detected, many of the radioisotopes are barely detectable at further distances. Measurements under different meteorological conditions give no evidence for preferred environmental
pathways. The environmental atmospheric system is generally well mixed. During periods of inversions and calms no appreciable build-up of induced airborne radioactivity is observable over the region.

Although radioactivity variations of effluent water reflect the influence from operating the accelerators, general levels are low. The part of the rivulet into which the radioactive effluents are fed is lined. In addition to effluent water from the Laboratory it collects precipitation run-off and rivulet water from outside the Laboratory influence area. Thus radionuclide concentration of the water arriving in the natural stream bed is further diluted. Water eventually seeping into the root layer of plants experiences soil retention. It has been shown that for most of the induced radionuclides carried by water, soil retention is high.

Organic material can concentrate isotopes even if supplied in low concentration. However, assimilation and concentration in organisms depend on many parameters, in particular also on the natural trace element availability. Measurements of Be-7 in vegetation of the area, in particular in lichen, give a high concentration factor. This agrees with fallout studies of lichen. The concentration factor depends among other things on the plant geometry. For finely divided plants like those under study, high radionuclide concentration factors are expected. Although blank samples from outside the Laboratory influence area were available, discrimination against natural Be-7 content of the plants was not possible. For that purpose more systematic investigations of the trace element content, the physical, chemical and physiological factors involved are to be carried out.

From the results presented it can be concluded that the present operation of the CERN high energy accelerators gives rise to low level radioactive pollution of the environment. Although environmental receptivity for various induced isotopes was found to be largely different, it has been shown that at present the discharge from the source area does not exceed the general radiological capacities of the Laboratory site. Therefore, the influence zone of the Laboratory is mainly restricted to within its boundaries. Radiopollution of public environment due to Laboratory releases is smaller than the
contribution from natural and actual fallout radioactivity from nuclear bomb tests, and is small also compared with industrial pollution of the area. It has been reported in earlier studies that particle concentration of local air is comparable to that of cities like Paris\textsuperscript{23}).

Low radioactivity monitoring is difficult, costly, and time-consuming. Careful attention has to be given to how detailed, at which locations, and over what time intervals information is required. Considerations regarding choice of location, equipment and methods for controlling radiopollution near high energy accelerator installations have been discussed in the light of present recommended acceptable limits. The number of fixed installed monitoring stations can be kept low on the CERN Laboratory site. Their locations are considered to give representative data for the site. Instrumentation methods used to carry out the presented work are suitable for providing general information on the actual environmental radiation situation of the site under study. It was found particularly useful and necessary to obtain continuous information on total beta activities and isotope concentrations. The latter are mostly satisfactorily obtained from \(\gamma\)-ray spectroscopical analyses with a Ge(Li) detector. When the isotope mixture has a significant soft beta component, Rb-87 counter calibration is recommended. The stations are regularly visited for maintenance requirements and background controls.

Meteorological instrumentation and automatic air monitors performed satisfactorily and yielded reliable data. The automatic water monitoring system needs reconsideration. Although it is felt useful to have continuous data on total beta activity of the effluent water, it has to be noted that a number of induced volatile radioisotopes get lost during sample fixation on the monitor tape. The performance of the monitor has become more reliable after several modifications applied to overcome its mechanical and electrical shortcomings.
The objective of this study was to clarify the question of the extent to which operation of the high energy accelerator installations influences the environment. The quoted data holds for operating and specific environmental conditions of the Laboratory site during 1967-1970. Significantly different values are to be expected for different operational modes and environmental conditions. Exploitation of the accelerator facilities at higher intensities will not significantly affect public environment so long as the radiological capacity of the site is not exceeded and the level of stray radiation escaping into the open does not appreciably increase.

At this stage of the program effort should go into studies of groundwater radioactivity and into controls of individual isotopes including A-41, Ca-45, H-3, and various long-lived products. The formation of ozone and aggressive agents should be investigated and methods be developed for routine monitoring.

Concentrations of natural isotopes produced from cosmic rays are mostly low. Detection difficulties are the reason that their environmental behaviour is largely unknown. High energy accelerators produce many of these isotopes which can escape into the environment in measurable quantities. Useful additional information on creation, dispersion and behaviour on their pathways can be obtained from induced radioactivity investigations in the environment of high energy accelerator installations.
ACKNOWLEDGEMENTS

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This report is dedicated to the memory of the late Mr. A. Prantl, father of Dr. F.A. Prantl, whose continued personal interest provided her with encouragement in all aspects of her work.
REFERENCES


3. F.E. Hoyer, Induced radioactivity in the earth shielding on top of high-energy particle accelerators, CERN 68-42 (1968).


Table 1

Mean annual wind directions and speeds

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# Table 2

Details regarding measurements at CERN of radioactivity in aerosol, precipitation and effluent water

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HP = Health Physics
PS = Proton synchrotron
SC = Synchro-cyclotron
WM = Water monitors
FIGURE CAPTIONS

Fig. 1. Locations of the various monitoring stations on the CERN Laboratory site, average net annual dose recorded.

Fig. 2. Calibration curves of the total β activity counters.

Fig. 3. Location of movable air suckers for sampling experiment January-September 1970.

Fig. 4. Example of γ-ray spectra from samples collected during normal accelerator operation and during shut-down.

Fig. 5. Mean values of total γ, Be-7 activity and particle concentration for the air sampling experiment from January-September 1970.

Fig. 6. Total β activity of air at CERN and some other European monitoring stations from August 1969 to August 1970.

Fig. 7. Total β activity of precipitation at CERN and some other European monitoring stations from December 1968 to May 1969.

Fig. 8. Example of a γ spectrum of a snow sample collected near the CERN Synchro-cyclotron.

Fig. 9. Total β activity discharged by the main effluent 1 (pCi/l), and monthly amount of precipitation collected into this effluent from August 1969 to August 1970.

Fig. 10. Monthly total β activity discharged by the main effluent 1 (mCi), monthly amount of accelerated protons (p/a) at CERN, and total β activity deposited by precipitation (Mol, Belgium) (mCi/cm²) between August 1969 and August 1970.
CALIBRATION OF TOTAL $\beta$ ACTIVITY COUNTERS

Rb-87 $E_{\text{max}\beta} = 0.275$ MeV
K-40 $E_{\text{max}\beta} = 1.35$ MeV

KCl CALIBRATION METHANE FLOW COUNTER
0.5 mg/cm$^2$ WINDOW THICKNESS STEEL PLANCHETS 2'' DIAMETER

KCl CALIBRATION GM COUNTER
PLASTIC PLANCHETS 1'' DIAMETER

RbNO$_3$ CALIBRATION GM COUNTER

SAMPLE THICKNESS

Fig. 2
Fig. 3

LOCATION OF MEASUREMENTS OF AIR ACTIVITY
July - Sept. 1970
Fig. 5
Total $\beta$ activity of air at CERN and some other European monitoring stations from Aug. 1969 - Aug. 1970

Fig. 6
Total $\beta$ activity of precipitation at CERN and some other European monitoring stations from Dec. 1968 - May 1969

![Graph showing total $\beta$ activity of precipitation at CERN and other European monitoring stations from Dec. 1968 to May 1969. The graph plots pCi/l on the y-axis against dates from December 1968 to May 1969. The stations include CERN, Mol, Belgium, and Vesinet, France. The graph data points indicate an increase in activity over the stated period.]
--- total $\beta$ activity of drainage water from the main CERN effluent 1, (pCi/l).

- monthly total $\beta$ activity discharged by the drainage water of the main CERN effluent 1 (mCi).
- monthly amount of accelerated protons (p/a) at CERN and total $\beta$ activity deposited.
- precipitation at Mol, Belgium (mCi/km$^2$) between Aug. 1969 and Aug. 1970.

**Fig. 10**