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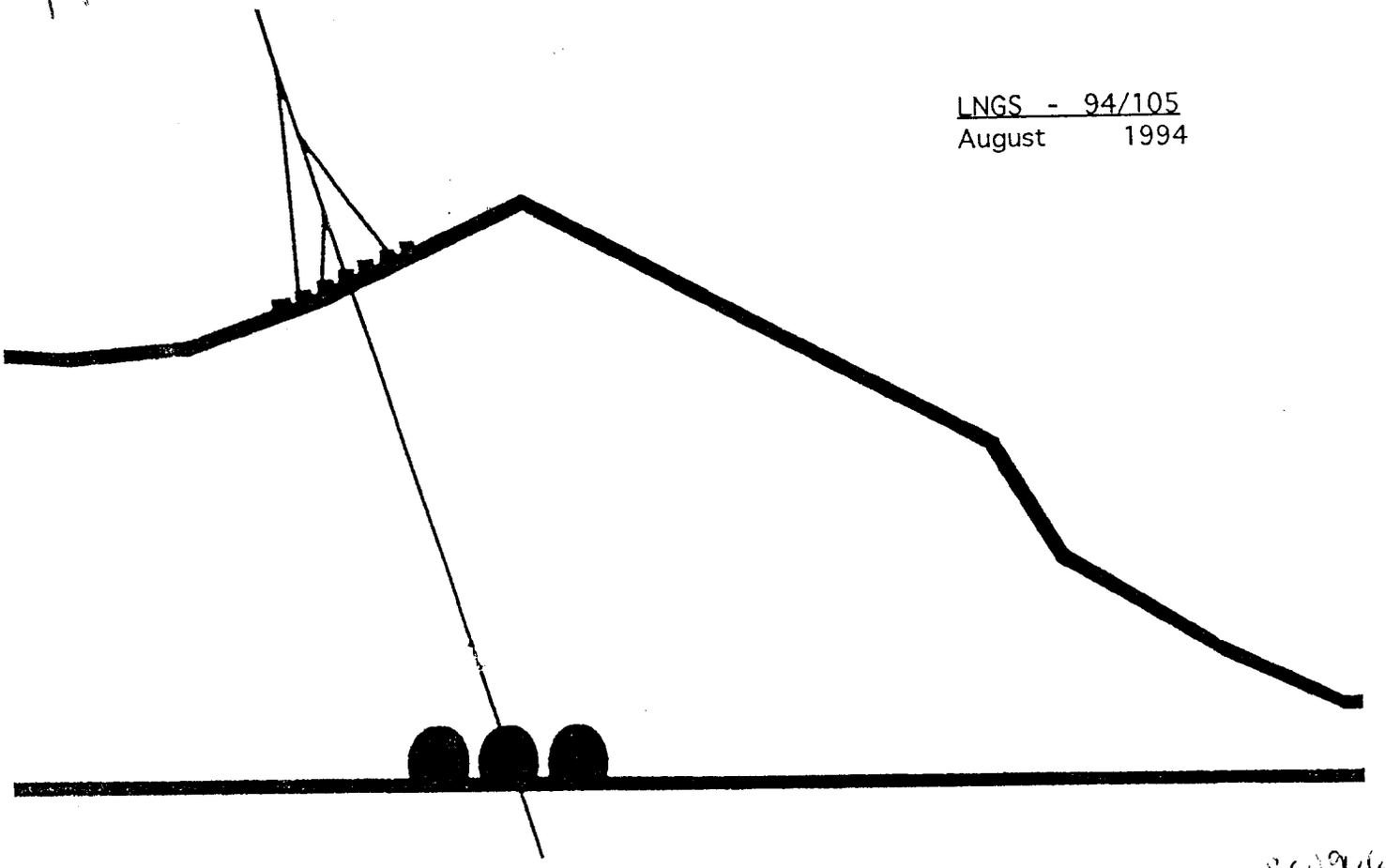

LNGS - 94/105
August 1994

SW9445

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*) *to be submitted to Health Physics*

INFN - Laboratori Nazionali del Gran Sasso

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RADON MEASUREMENTS IN THE GRAN SASSO UNDERGROUND LABORATORY

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ABSTRACT

Data on radon measurements in the Gran Sasso Underground Laboratory (LNGS) are presented. The influence of the new air ventilation system is also discussed.

The data were obtained with different methods and the leading characteristics are compared. The general level of the radon concentration in the Gran Sasso Laboratory has been significantly reduced by the new ventilation system.

In the LNGS report, two appendices (one in English and one in Italian) have been added in order to better explain the effects of radiations from radon.

To be submitted to Health Physics

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RADON MEASUREMENTS IN THE GRAN SASSO UNDERGROUND LABORATORY

1. INTRODUCTION

The Gran Sasso Underground Laboratory (LNGS), dedicated to astrophysics , nuclear and particle physics experiments, consists of three halls excavated transversally to the 10.4 km tunnel that goes through the Gran Sasso massif, in central Italy, and connects with a double highway L'Aquila (SW) with Teramo (NE). The three halls are conventionally named A, B and C; service and safety tunnels complete the underground laboratory (see the layout in fig.1).

Due to the importance of reducing all possible contributions of radiation doses to the laboratory personnel and to reduce background radiation for the experimental apparatus, a constant monitoring of radon gas has been carried out.

Although, the radium concentration of the Gran Sasso rock is low [1], the rock permeability and the large amount of water present in the massif favour radon transportation and accumulation into the laboratory. Water drainage and insulation of the internal walls has been provided to prevent excessive concentrations. Now, the only possible reduction of the radon concentration is by means of an efficient ventilation system. We followed the modifications carried out during the last two years in the laboratory ventilation system. The improvement in reducing radon concentration indicates that the air ventilation system modifications inside the laboratory were effective.

Before July 1993, the ventilation system was designed to take in air from the road tunnel and to eject old air from the laboratory into a 4 km pipe leading outside the road tunnel towards Teramo. The air intake was about 15000 $m^3 h^{-1}$ in each of Hall A and B.

Approximately one month before the opening of the second highway tunnel to the general traffic, the air ventilation in the underground laboratory was reversed and several ventilation tests were carried out. At the opening of the highway on July 29, 1993, a reasonably stable new ventilation system was already set in the laboratory. Since 24 July 1993, the air flow is reversed: fresh air is pumped in from outside the gallery on the Teramo side through the pipe. The average volume of air pumped into the laboratory halls is approximately 40,000 $m^3\ h^{-1}$ (of which about 10,000 $m^3\ h^{-1}$ in Hall B). In case of emergency, the air flow may be reversed and the air and eventual dangerous gases (e.g. halon) in the laboratory may be expelled. Further improvements in air flow and air conditioning where made at the beginning of 1994 and the air flow is presently steady at 35,000 $m^3\ h^{-1}$ and uniformly distributed throughout the whole underground lab.

The radon measurements reported here refer to the period from June 1993 till June 1994. In Appendix A are briefly recalled some radiation protection aspects regarding radon induced lung cancers.

2. MONITORING METHODS

Radon measurements are relatively delicate; in order to obtain absolute concentration levels, careful calibrations are needed, but the precision is usually not better than 10% [2, 3]. The radon content in the air is highly dependent on several factors, the main one being ventilation. Because of the uncertainties and fluctuations, we tried to compare different methods [4,5]. For each commercial instrument, the calibration was performed directly by the vendor. For other methods, like CR-39, the calibration was performed at the NRPB laboratory by our team, the Pylon instrument was calibrated at the ENEA center in Casaccia, Roma; the Lucas cells were calibrated at the AGIP laboratory in S. Donato Milanese. The Atmos detector was calibrated by the producer. The different methods were cross calibrated in 1990-91 [4,5]. Presently most measurements are performed with two Pylon chambers, an Atmos instrument and Lucas cells. Alpha spectrometry and the Markov method for radon progeny measurements were also used. We recall briefly the different methods used.

a) Pylon and Atmos Chambers.

We recall that the pylon method was developed by the Pylon Electronic Development Company of Canada.

Filtered air is pumped into an electrostatic chamber in which the negative electrode at -1000 V is a thin conductive mylar foil placed on a ZnS scintillator, used for alpha particle detection [2]. Alpha counting is performed three hours after the end of each air

sampling. We used regularly two commercial Pylon instruments located in Hall B and in Hall A. A commercial Atmos instrument (ionization chamber) developed by Gammadata Matteknik AB, SWEDEN with 10% standard deviation sensitivity at 800 Bq m^{-3}, is used in Hall C. Its sentivity is about 10 Bq m^{-3}.

b) Solid State Alpha Spectrometry.

A known volume of air is forced through a filter [2]. The radon daughter concentration in the air sample is measured through alpha spectrometry of the filter using a solid state detector. This method, with the SILENA, Milano, commercial instrument, now is not used continuously but only every few months.

c) CR39 Nuclear Track Detectors.

With this method air freely diffuses into a special container where alpha particles are registered on a CR39 nuclear track detector [6]. Minimum exposure times of the order of one month were required for the radon concentrations present in the laboratory air. The CR39 detectors were etched and analysed at the INFN laboratory in Bologna. This method was extensively used at the beginning of the radon monitoring, in 1990. It was later limited to cross calibration purposes only. The detectors were calibrated in a radon chamber at the National Radiological Protection Board (NRPB) in Chilton, UK. The calibration factor is 1 track per cm^2 per month of exposure equivalent to 0.41 Bq m^{-3} , with about 13% precision [6].

d) Active Carbon Detectors.

Air diffuses into a canister where radon gas is adsorbed by active carbon. Sampling lasts 2-4 days; then gamma rays emitted by the radon progeny captured into the active carbon are counted by means of a scintillation detector [7]. This method was extensively used through 1990-92; the active carbon detectors were fabricated and analysed by a specialized laboratory in the USA [7]; the samples are calibrated to about ± 15% precision [6,7].

e) Lucas Cells.

They consist of glass or transparent plastic bottles (cells) internally coated with ZnS [8]. Just before sampling, vacuum is created in the cell. Then a filtered air sample is freely let into the cell. A delay of at least 3 hours is needed before placing the cell in optical contact with a photomultiplier in order to detect alpha particles emitted by radon and its daughters. The system sensitivity is about 4 Bq m^{-3} with a calibration uncertainty

of about 10%. Measurements obtained with a set of cells from AGIP were originally compared with those obtained with cells from the University of Drexel. Now only the AGIP cells are regularly used.

f) Markov Method.

This method is based on two successive alpha particles counting of a glass fiber filter through which a known air volume has been previously forced[2]. The potential alpha energy concentration is obtained with this technique. Its precision is about 12%. Also this method was used extensively in the 1990-1991 measurements at Gran Sasso. It is now used only for cross checks.

3. RADON CONCENTRATION

The radon concentration was monitored in the locations indicated in Figure 1 and the data are shown in Figures 2-5 and in Table 1 and 2. The following considerations may be made.

1. Before reversing the inlet air flux in July 1993, the average value of the radon concentration was around 60 Bq m^{-3} in Hall B and 135 Bq m^{-3} in Hall C. At that time the gates of the laboratory were kept open letting air exchange between the laboratory and the road tunnel.

2. Many alterations took place in the last six months of 1993, mainly connected with the construction and testing of the new ventilation system.

3. After inverting the air flux in July 1993, the radon concentration decreased in Hall B to an average value of about 15 Bq m^{-3}; it stabilized at about 20 Bq m^{-3} after September 20, 1993 and it increased slightly at the end of 1993 (see Fig.3). In 1994 the radon concentration shows some steps at different levels. It now seems to average at about 20 Bq m^{-3}.

4. In Hall A, the radon concentration dropped like in Hall B, see Fig.2. Peaks may be noticed (also present in Fig.3) related to stops of the ventilation system, or to some inconvenients in the air ventilation or to the necessity of opening the gates for special deliveries. The radon monitoring is thus an effective monitoring of the air exchange. Further investigations are needed to understand unexpected variations.

5. In Hall C and in the connecting tunnels, the radon concentration increased from about 130 Bq m^{-3} before July 2, 1993, to 350 Bq m^{-3} in July and August 1993 because of the reduction of the ventilation in the tunnel. After September 20 and for the rest of 1993

the average concentration in Hall C and in the connecting tunnels was about 220 Bq m^{-3}. After the improvements made at the end of 1993 the concentration is now about 50 Bq m^{-3}.

6. The radon concentration decreased in the connecting tunnels and in Hall C when the small doors near the Guard Room were kept open for a certain time.

7. Since July 1993, in the laboratory a slight over-pressure is assured, of about 5 mm H_2O compared to the outside road tunnel.

8. At the end of July 1993, a slight variation in radon concentration between day and night was noticed; but the oscillations almost disappeared later on.

4. HUMIDITY, TEMPERATURE, PRESSURE AND AIR VENTILATION

These parameters were monitored with standard instrumentation and gave the following indications.

a) Relative Humidity (%)

	31/07/93	14/10/93	7/04/94	7/06/94	9/06/94
At the gas station in Hall B	90	47	33	57	67
Inside Attico of MACRO	61	41	28	48	54
In front of MACRO	76	46	37	56	65
In Hall A	75	50	38	70	72
In Hall C	67	59	53	82	88

b) Temperature (°C)

	31/7/93	14/10/93	7/4/94	7/06/94	9/06/94
In the air inlet in Hall B	16	-	17	19	20
Near the gas station in Hall B	18	17	15	22	22
Inside Attico of MACRO	20	20	22	26	26
In Hall C	20	16	14	16	17
In Hall A	19	17	16	19	21

c) Pressure (mbar)

	31/7/93	7/4/94	7/06/94	9/06/94
In Hall B	912	897	922	918
In Hall C	947	896	923	910
In Hall A	945	896	921	919

d) Volume of air ventilation ($m^3\ h^{-1}$)

	21/7/93	08/4/94	11/4/94	9/06/94
In Hall A	5870	5600	6830	-
In Hall B	8320	6840	8040	8000
In Hall C	-	13910	8440	-

It may be noted that most of the above parameters are within normal ranges. One of the exceptions is the higher level of relative humidity in the summer periods; the dehumidifier improvements made at the beginning of 1994 may have reduced this problem,

but not yet solved it. Note also that between the 7th and the 9th of June 1994 there were some problems with air ventilation and variations of the outside meteorological conditions.

5. CONCLUSIONS

One of the main results from the air flux inversion in July 1993 and of the improvements at the end of 1993, is the reduction of the radon concentration from 60 to 20 Bq m^{-3} in Halls A and B, which is quite acceptable from the point of view of the radiation protection standards and also for low energy experiments background. Unfortunately the situation is not completely stable and the present level of radon in Hall B is about 20 Bq m^{-3}. In Hall C, in the First Aid area and in the connecting tunnels, the concentration of radon increased to over 300 Bq m^{-3} in July 1993 soon after the inlet reversal; it became about 220 Bq m^{-3} in the fall of 1993 and it is now less than 100 Bq m^{-3}, about 50 Bq m^{-3} in Hall C and about 100 Bq m^{-3} in the service tunnels after the new ventilation system and the gate installation in Hall C.

Another consequence of the air flux inversion was a considerable increase of the relative humidity during the summer months because of the higher difference of the air temperature outside and inside the gallery. During that period the humidity was around 60-80%, which is too high for the electronics, in particular for that on top of MACRO. Dehumidification of the incoming air was deemed advisable, both at the Teramo pipe entrance and at the Hall A and B inlets during the hot season (while it may not be necessary during the winter). The improvements made at the end of 1993 should help in further reducing this problem. But it is not yet solved completely. It is clear that there still are problems connected with the controls of the ventilation and with the dehumidifier systems.

It has to be noted that in Halls A and B the air is only pumped in and not pumped out. Pumping out may be advisable. It is also highly recommended to check frequently the proper efficiency of the monitors used for controlling humidity, pressure, etc., as some of the instruments easily miscalibrate. The results show the importance of monitoring the radon concentration in the Halls and in the connecting tunnels. The situation is not stable yet, even if the mean values are quite acceptable for the personnel working underground.

6. ACKNOWLEDGMENTS

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Laboratory and AGIP-RADI for their cooperation. H. Dekhissi would like to thank the ICTP Program on Training and Research in Italian Laboratories for the fellowship.

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8. FIGURE CAPTIONS

Figure 1. General layout of the Gran Sasso Underground Laboratory; the locations of the radon measurements are indicated.

Figure 2. Results of the measurements of the radon concentrations with the Pylon instrument in Hall A for the period 3/6/93 - 17/02/94. The measurements were averaged over the day.

Figure 3. Radon concentrations measured with the Pylon instrument in Hall B in front of MACRO for the 1/6/93 - 6/7/94. During some periods, the Pylon instrument was off.

Figure 4. Radon concentrations measured with the Atmos instrument in Hall C for the period 27/07/93 to 30/05/94.

Figure 5. Radon concentration controls made with Luca' s cells in different areas of the underground laboratory. For locations see Fig.1.

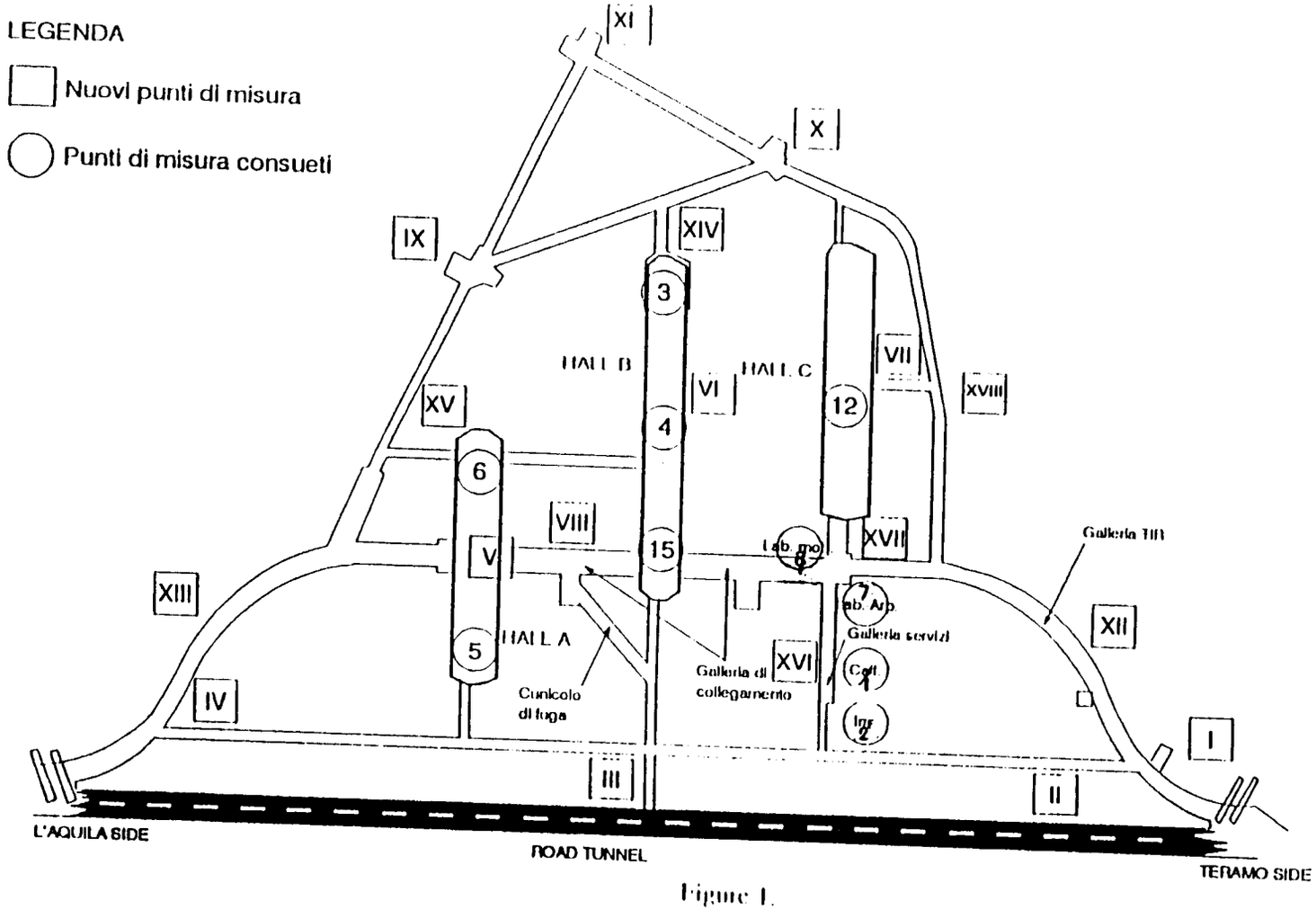
Table 1. Measurements by Pylon instrument in Hall "A". Unit of radon activity is Bq/mc

Month/date	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
June	103	99	69	34	43	55	65	62	68	48	46	49	48	76	94	58	44	57	67	63	67	41	41	70	58	66	42	69	80	60	
July	60	68	59	42	44	92	54	29	49	54	48	39	69	65	48	49	23	36	33	52	98	63	107	54	15	24	21	26	41	30	12
August	9	11	12	13	13	18	17	13	13	11	14	10	26	9	13	15	13	13	15	12	10	11	19	13	16	14	11	9	9	11	13
September	31	13	12	10	23	11	12	9	11	13	12	9	11	12	19	16	16	15	22	21	20	21	36	25	18	14	13	16	16	32	
October	74	27	16	21	30	25	23	29	25	38	50	33	21	21	18	22	19	27	24	28	46	42	26	20	30	23	22	18	22	17	16
November	18	41	17	17	20	14	12	32	33	17	14	20	14	11	27	15	13	22	66	118	105	112	151	151	172	62	25	20	18	13	
December	16	30	46	62	17	13	17	12	16	12	11	10	21	15	13	17	24	21	22	25	31	19	20	24	25	26	27	36	38	109	81
January	48	42	45	61	52	31	36	32	32	60	63	36	21	12	14	19	15	14	17	16	21	13	12	10	12	16	15	14	11	*	*
February	*	*	17	28	16	13	19	17	21	27	15	13	13	14	19	25	31	*	*	*	*	*	*	*	*	*	*	*	*	*	*

Table 2. Measurements by Pylon instrument in Hall "B". Unit of radon activity is Bq/mc

Month/date	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
June	75	70	102	146	86	105	119	100	72	76	78	79	55	49	70	93	57	44	51	60	59	65	45	41	56	53	49	43	53	59	
July	51	70	51	46	46	58	39	28	41	43	43	33	60	59	47	35	24	27	28	34	55	39	61	43	19	27	35	34	41	24	19
August	13	20	15	15	15	24	17	16	16	16	16	15	14	15	13	12	14	8	*	*	*	*	*	*	*	*	*	*	*	*	*
September	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	15	14	14	16	17	17	18	26	25	19	13	16	17	17	18	
October	15	15	15	20	21	19	19	24	17	18	23	32	32	28	24	21	18	19	22	23	26	22	19	16	19	18	19	22	19	18	17
November	19	23	39	22	22	17	15	18	18	15	17	16	14	13	20	22	17	18	30	48	39	37	53	36	36	36	32	26	26	24	
December	23	22	27	44	15	17	17	13	15	21	17	14	16	20	24	25	19	17	15	18	23	34	21	21	22	22	23	24	28	30	61
January	31	36	29	27	32	31	30	25	25	28	28	27	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
February	29	31	35	37	31	32	29	28	28	27	26	26	27	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
March	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
April	*	*	*	*	*	*	*	18	21	14	13	15	19	16	15	19	41	16	18	14	16	17	18	18	15	16	17	35	38	42	
May	41	45	17	13	14	38	40	39	44	44	44	42	42	41	41	41	47	54	51	38	35	37	40	41	43	39	39	38	38	40	63
June	78	79	84	92	99	72	55	56	31	18	16	23	34	36	17	17	17	13	20	20	29	30	24	25	19	19	20	20	22	20	
July	18	18	24	20	14	13																									

GRAN SASSO UNDERGROUND LABORATORIES



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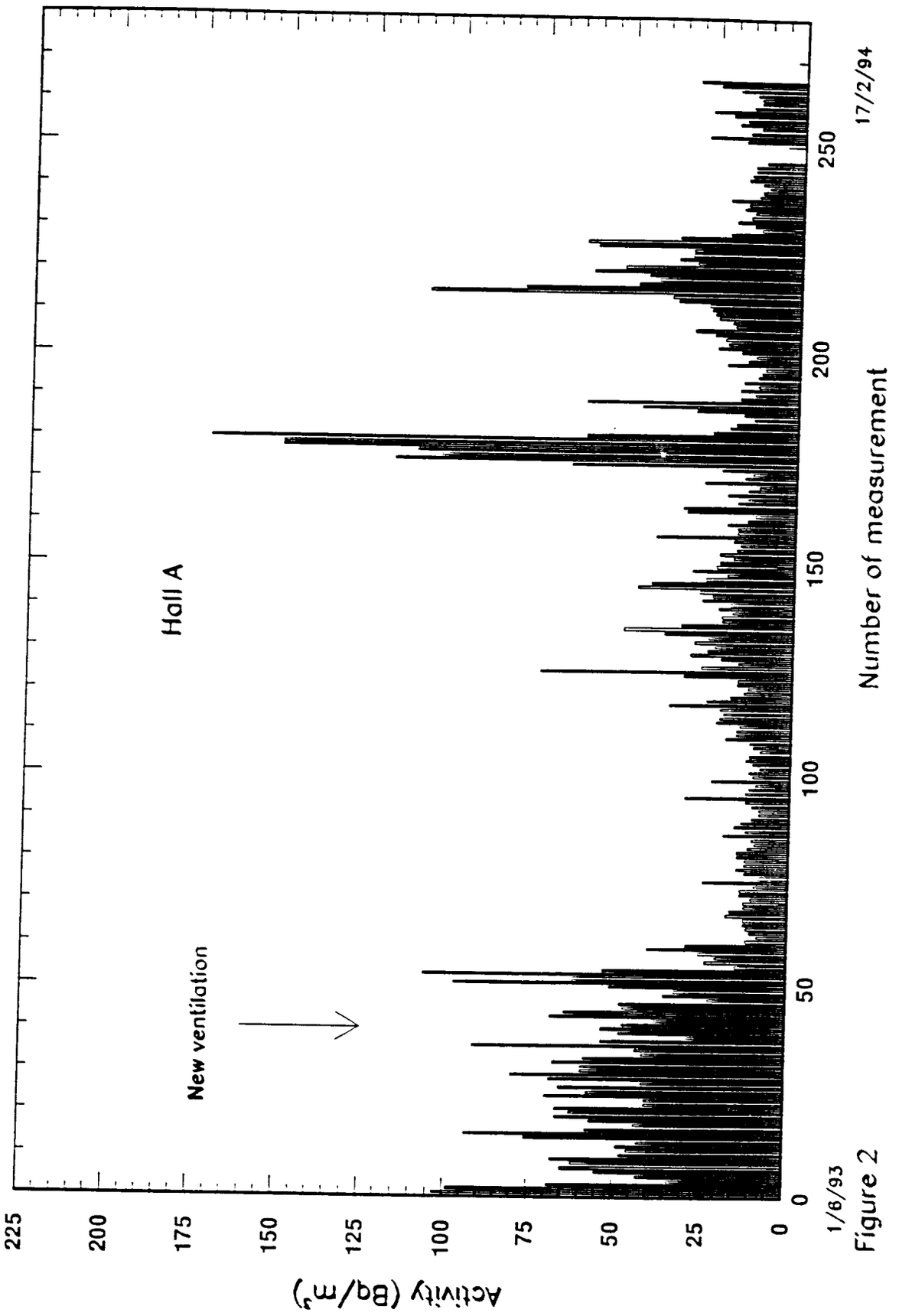
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200
175
150
125
100
75
50
25
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50
100
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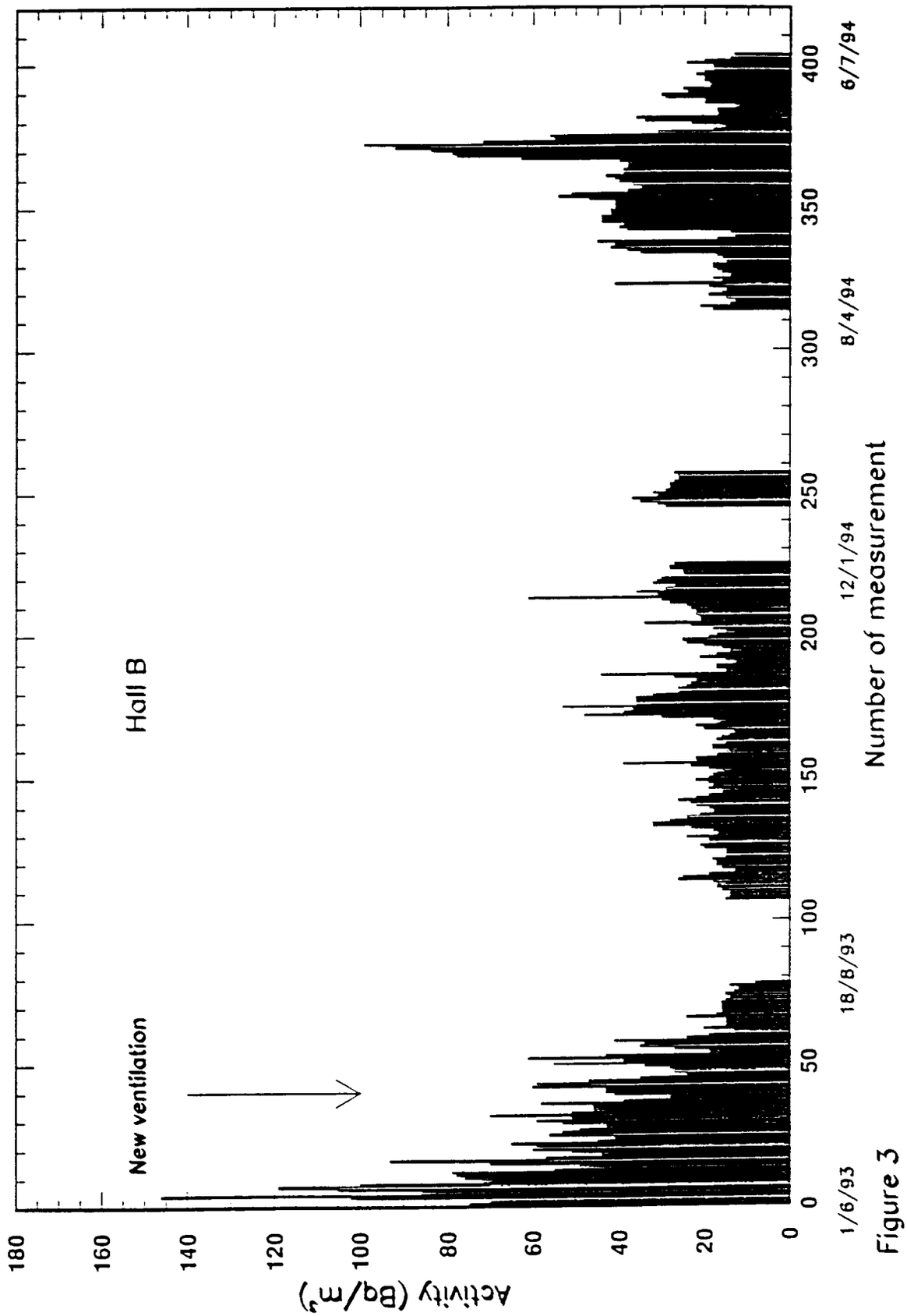
200
250
Number of measurement
1/6/93
17/2/94

Figure 2


Hall B
New ventilation
Activity (Bq/m³)
Number of measurement
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40
60
80
100
120
140
160
180
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200
250
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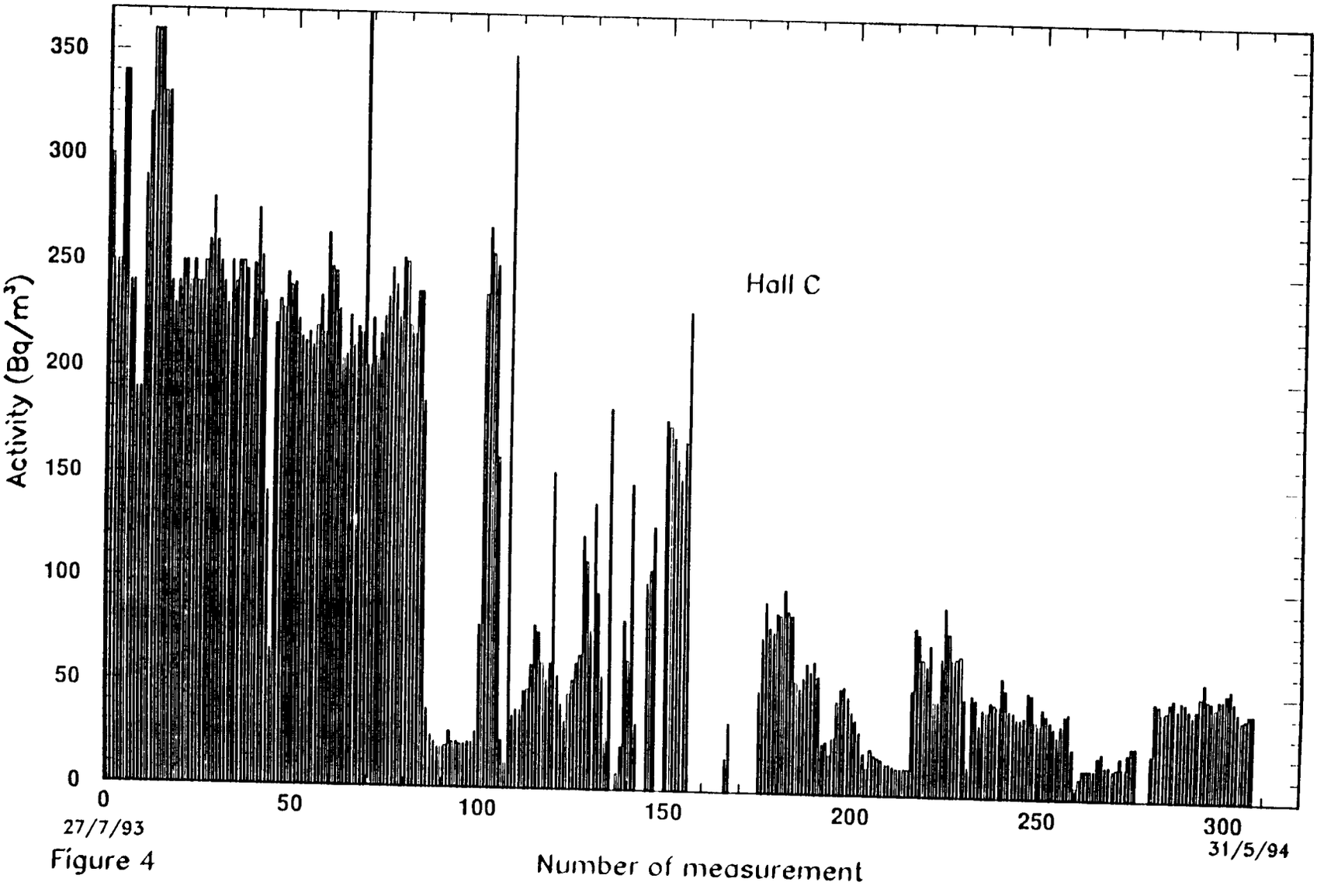
1/6/93
18/8/93
12/1/94
8/4/94
6/7/94

Figure 3


Activity (Bq/m³)
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300
250
200
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100
50
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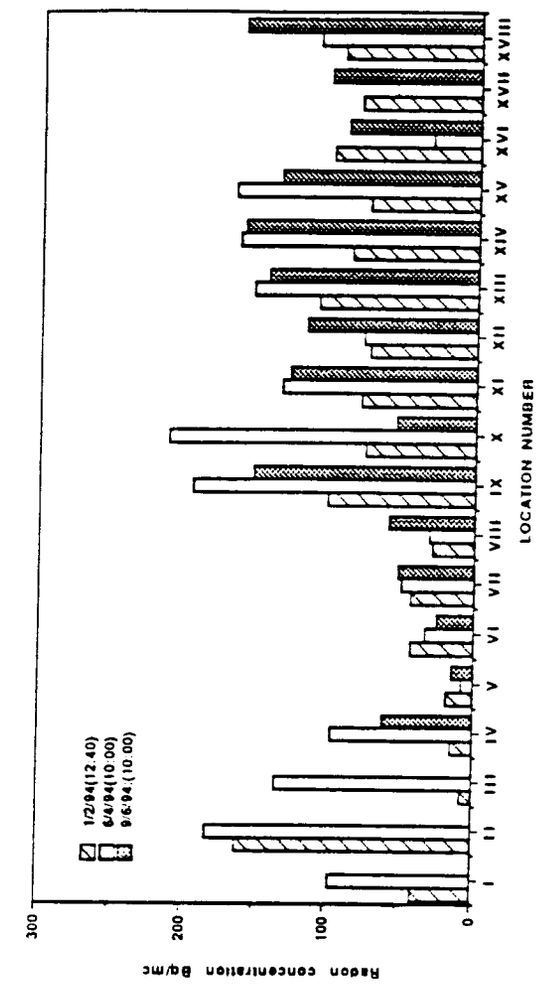
Hall C
0
50
100
150
200
250
300
27/7/93
31/5/94
Number of measurement

Figure 4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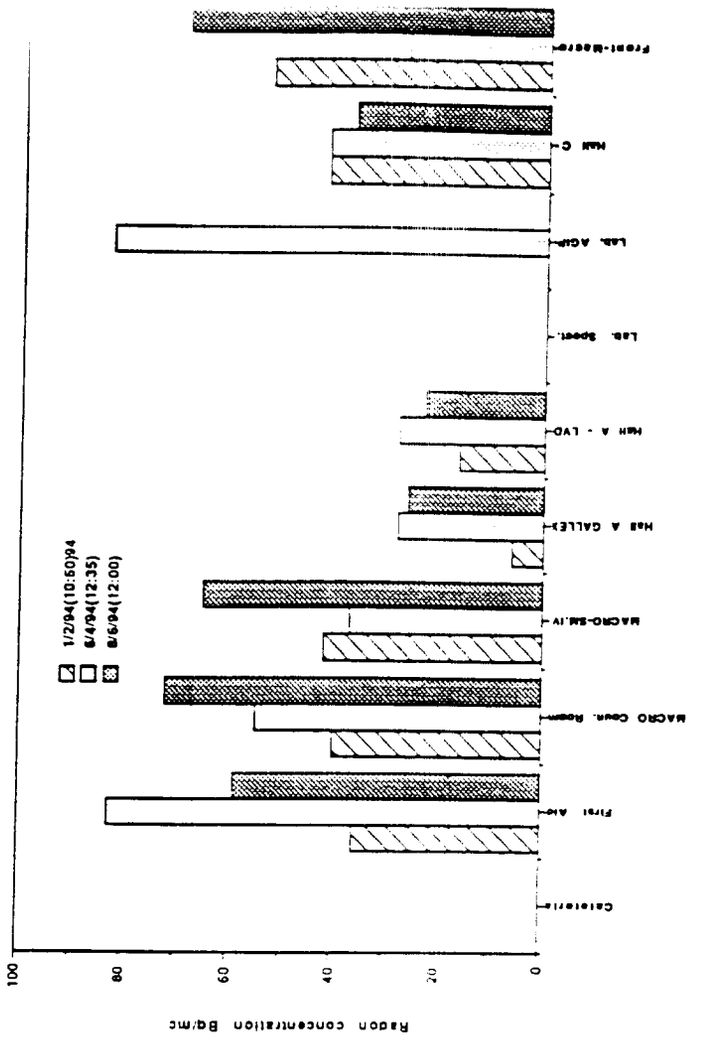
LOCATION NUMBER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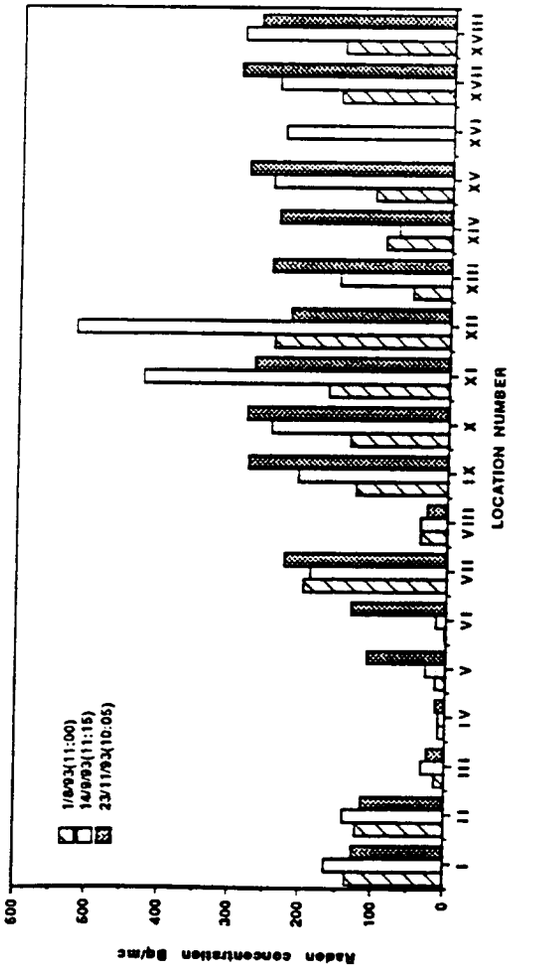
Radon concentration Bq/mc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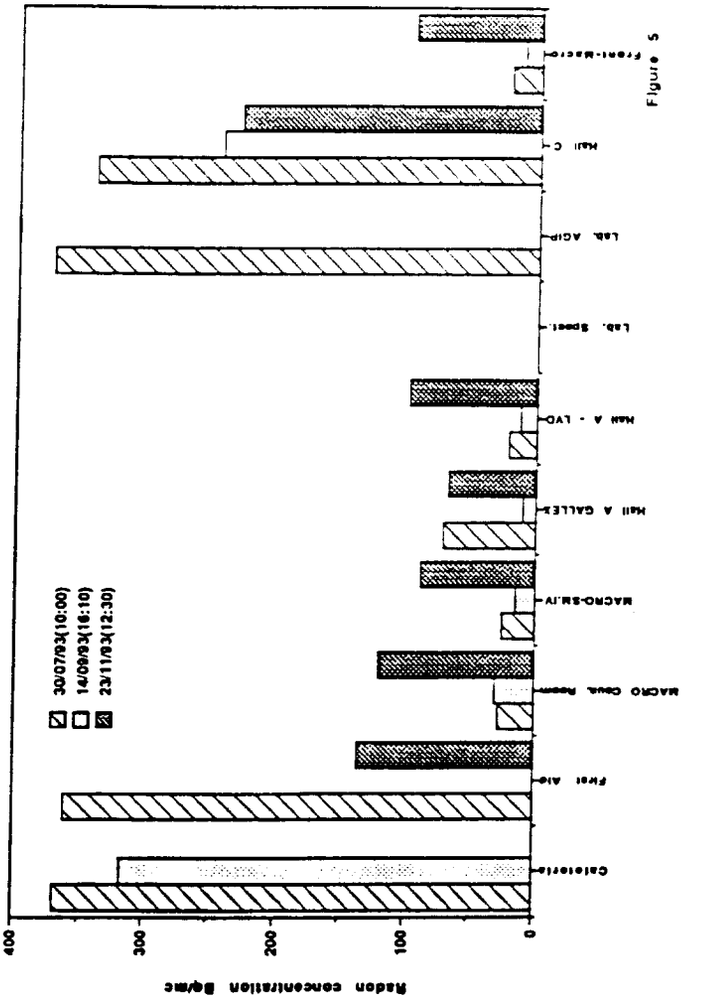
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23/11/93(12:30)
Radon concentration Bq/mc

Figure 5

Appendix A. Radiation protection aspects regarding the probability of induced lung cancer from exposure to radon and radon progeny[9].

There exists an association between exposure to radon and lung cancer. Inhaled short-lived radon daughters, being alpha emitters, contribute the major part of the effective dose* to the population due to the natural background of ionizing radiations.

Epidemiological studies of miners and laboratory data allow us to characterize the risk of fatal lung tumors associated with radon and its short-lived daughters present in indoor domestic environments (there has been great interest in this problem for about a decade).

Most radon progeny attach to particles suspended in air (aerosols). The unattached fraction is a direct source of the dose received by the cells of the whole respiratory tract, while the aerosols contaminated by radon deposited in the respiratory tract depending on their size and on other chemical and physical parameters. In conclusion, the distribution of the radon progeny in the tracheobronchial and alveolar regions is rather uncertain. Therefore, extrapolations from existing data must be cautiously weighted when used for general condition estimation.

International scientific organizations considered all the possible different parameters involved in the problem and associated the relative health effects on workers and population in order to point out optimal "risk to benefit" relationships (Table A1).

Radon concentration monitoring for dwellings revealed measurements spread over a very wide range, starting from few becquerels per cubic meter up to 10^5 times as much, that is up to concentrations found only in uranium mines in the old times. The overall world average for indoor radon seems to be close to 15 Bq m^{-3} which brings to a risk of 15-20 fatal cancers per million inhabitants (risk factor approximately 1-1.4 10^{-6} per Bq m^{-3}).

Remedial actions are recommended only when indoor concentration exceeds 10-20 times the global average. Higher concentrations may be accepted in work places where the maximum occupancy is taken as 170 hr per month (approximately 2000 hr per year). As a general safety standard in radiation protection, the risk acceptability for population is set at least 10 times lower than that for workers.

Conventionally, the Working Level (WL) is used to measure the concentration of radon daughters present in the inhaled air. The WL is defined as the combination of short-lived radon daughters in one liter of air that results in the ultimate release of $1.3 \cdot 10^5$ MeV of potential alpha energy. This is approximately equivalent to the energy emitted by the short-lived daughters in equilibrium with 100 pCi (3.7 Bq) of radon.

For cumulative exposures, the Working Level Month (WLM) is used. This expresses the exposure due to the inhalation of air with a concentration of 1 WL for 170 working hours. In the International System (SI) of units, 1 WLM = $3.5 \cdot 10^{-3}$ J h m^{-3} = 3.5 mJ h m^{-3}.

On the basis of different dosimetric models, it is estimated that the mean alpha dose absorbed** by the tracheo-bronchial tissue per unit of indoor exposure ranges from 4 to 13 mGy, equal to 1.2-3.7 Gy per J h m^{-3} per WLM. All the studies carried out so far, indicate a proportional increase of the excess cancer frequency with the cumulative exposure to radon progenies up to levels of about 500 WLM. Statistically significant data of an increased lung cancer incidence are detectable only at minimum exposures of about 50 WLM. This level is approximately 2-5 times higher than the mean lifetime exposure of populations from indoor radon.

As far as the risk of lung cancer associated with living indoor is concerned, there are different projection models, but all of them refer to observations of miners. This implies that there are various difficulties in transferring the miner parameters to population condition. In general, a higher relative specific risk results for young people and apparently distant exposures carry less weight than more recent ones.

Overall evaluations refer to a life expectancy at birth of about 70-80 years and to average data for both sexes, without separating smokers from non smokers; the cancer probability coefficients given are roughly 1-4 $\cdot 10^{-4}$ per WLM , or 3-10 $\cdot 10^{-3}$ per mJ m^{-3} over a full lifetime. The large uncertainty in the values is due to the brief period of the epidemiology regarding this problem. Preliminary indications[10] on smoking influence drive to the conclusion that , the lifetime cancer risk due to exposure to radon progeny could be 6-10 ten times higher for strong smokers compared to non smokers.

The scientific literature on the whole topic is growing very fast and recently a compilation of average radon levels in living areas of U.S.A. has been provided in useful maps (Fig. A1 [11]). A wide investigation on the radon levels in the Italian territory has been completed and the data are being published [12].

* Effective dose=Absorbed dose multiplied by the radiation weighting factor and by the tissue weighting factor. These factors are needed to estimate potential health effects from exposures to radiations with different energy release concentration and/or from non-uniform body exposures. The radiation weighting factor, in operative radiation protection, ranges from 1 to 20 (indicatively 1 is for standard x-rays and 20 for alpha particles). The tissue weighting factor is given in percentage of the risk to the whole body and is used when only parts of the body are exposed. The weighting factor for the lungs is 0.12.

** Absorbed dose= Energy released per unit mass (1 Gy= 1 J kg^{-1}).

Table A1 [9]. Lifetime probability of fatal lung cancer due to lifetime exposure to radon progeny.

Evaluation	Projection Model	Probability of cancer death		
		Per Unit Exposure[1] (10^{-6} /WLM)	Per Unit Exposure[1] (10^{-3} /J h m^{-3})	Per unit of Inhaled Energy[2] (10^{-3} / joule)
NCRP, 1984b	Modified Absolute	130	37	31
ICRP, 1987	Absolute Constant	150	43	36
	or constant relative	230[3]	66[3]	55[3]
EPA, 1986 (Puskin and Yang, 1988; Puskin and Nelson, 1989)	Constant relative	115-400[4]	33-110[4]	27-95[4]
UNSCEAR, (1977; 1988b)	Arithmetic estimate	150-450	43-128	36-110
BEIR IV (1988)	Modified relative	350[4]	100[4]	83[4]

[1] Potential alpha energy exposure.

[2] Potential alpha energy inhaled.

[3] Referring to a global reference population with a baseline lung cancer rate of 400 cases/10^6 persons per year averaged over all ages and both sexes.

[4] Referring to the population of the U.S.A. only.

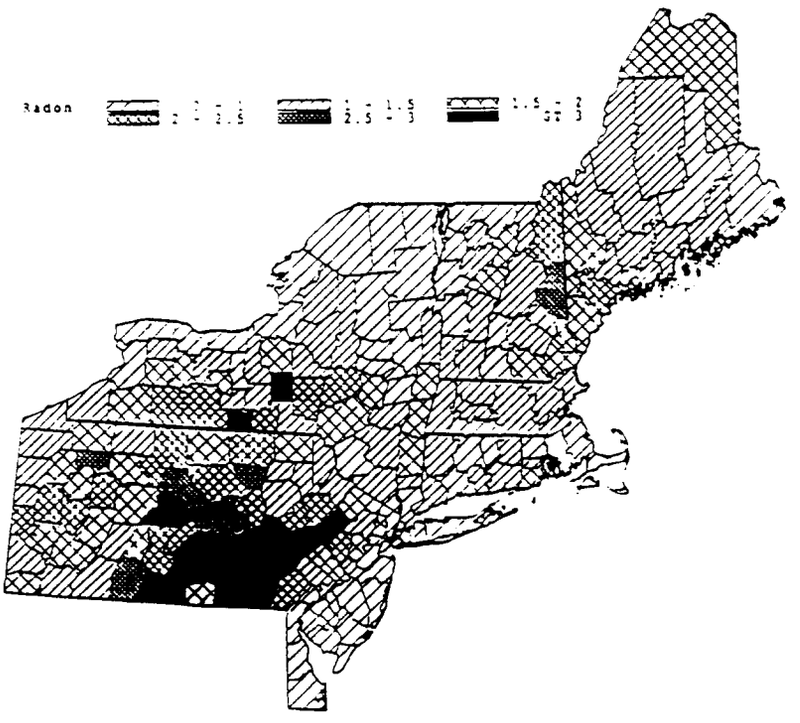


Figure A1. Map of average home radon levels in counties in the northeast of the US. Levels represented by various types of cross-hatching are shown in the legend in unit of r_0[10], $r_0 = 37$ Bq m^{-3}. Note: GT=greater than .

APPENDICE B: Radon nelle abitazioni e nei posti di lavoro e rischio alla salute

Il radon è un elemento radioattivo a molecola monoatomica prodotto dal decadimento di radionuclidi naturali presenti nella crosta terrestre. Appartiene alle grosse famiglie radioattive naturali di cui è l'unico rappresentante gassoso. Come gas è inerte (gas nobile), ha un peso specifico molto maggiore di quello dell'aria e tende a stratificarsi in basso. Ha discendenti ancora radioattivi e solo di recente si è prestata la necessaria attenzione al fatto che i prodotti di decadimento a breve vita del radon sono la più importante sorgente di esposizione naturale per i tessuti delle vie respiratorie.

La presenza più o meno elevata del radon negli ambienti confinati (indoor), quindi anche nelle case, dipende principalmente dal rateo di emanazione del radon dal suolo sottostante, dal contenuto di radio nei materiale da costruzione, dalle caratteristiche di diffusione all'interno dei locali e dalle condizioni di ricambio dell'aria degli ambienti stessi.

Il radon discende direttamente dal radio i cui sali sono molto solubili e può quindi essere trasportato nelle case anche attraverso l'acqua corrente. Il radon ha vari isotopi: il Rn-222 prodotto dal radio 226 della serie dell' U-238, il Rn-220 detto thoron perchè derivante dalle serie del Th-232, il Rn-219 della serie degli attinidi con capostipite l'U-235 e da ultimo il Rn-218 dal Th-226. Quello che si accumula maggiormente nei nostri ambienti è il primo perchè ha tempo di dimezzamento più lungo (3.8 giorni contro 55 secondi del Rn-220, 4 secondi del Rn-219 e 35 millisecondi del Rn-218).

Tabella B1

Decay properties of radon-222 and short lived progeny

		Main radiation energies and yields (y)					
		Alpha		Beta		Gamma	
Radionuclide	Half-life	Energy (MeV)	y (%)	Energy (max) (MeV)	y (%)	Energy (MeV)	y (%)
^{222}Rn	3.824 days	5.49	100	—	—	—	—
^{218}Po	3.05 min	6.00	100	—	—	—	—
^{214}Pb	26.8 min	—	—	1.02	6	0.35	37
				0.70	42	0.30	19
				0.65	48	0.24	8
^{214}Bi	19.9 min	—	—	3.27	18	0.61	46
				1.54	18	1.77	16
				1.51	18	1.12	15
^{214}Po	164 μs	7.69	100	—	—	—	—

Sources: Browne and Firestone (1986) and ICRP (1983).

Nella Tabella B1 sono riportati i discendenti a breve vita del radon 222 e le loro caratteristiche di decadimento.

Dal Po-214 si passa al Pb-214 che ha un tempo di dimezzamento di oltre 20 anni e, quindi, non interessa più dal punto di vista della dose assorbita dall'individuo che inala il radon. Comunemente, tutta l'energia rilasciata dai radionuclidi a breve vita viene definita "energia alfa potenziale" *(tabella B2).

Tabella B2

Potential alpha energy per atom and per unit activity

		Potential alpha energy			
		Per atom		Per unit of activity	
Radionuclide	Half-life	(MeV)	(10^{-12} J)	(MeV Bq^{-1})	(10^{-10} J Bq^{-1})
Radon (^{222}Rn) progeny:					
^{218}Po	3.05 min	13.69	2.19	3615	5.79
^{214}Pb	26.8 min	7.69	1.23	17 840	28.6
^{214}Bi	19.9 min	7.69	1.23	13 250	21.2
^{214}Po	164 μs	7.69	1.23	2×10^{-3}	3×10^{-6}
Total (at equilibrium), per Bq of radon				34 710	55.6

La frazione di radon respirato può essere libera o adsorbita sulla polvere (attached fraction) sospesa in aria, nel qual caso essa viene depositata sulle vie respiratorie in funzione della granulometria della polvere stessa. Le particelle di aerosol che raggiungono gli alveoli vengono trattenute per tempi lunghissimi a causa dei lenti processi di clearance polmonare.

* Dato il breve tempo di dimezzamento dei prodotti di decadimento, le particelle alfa rilasciate producono un forte addensamento di energia trasferita per cui la dose assorbita, che è misurata in gray (1 Gy= 1 $J\ kg^{-1}$), deve essere corretta per un fattore che tenga conto della distribuzione lineare specifica dell'energia e quindi della diversa *efficacia biologica* rispetto alle radiazioni x o gamma. Per le alfa, tale fattore, che è rapportato ad una radiazione di riferimento x o gamma, è circa 20. Cioè l'effetto biologico provocato con 0.05 Gy di radiazione alfa è equivalente all' effetto di 1 Gy di radiazione gamma.

Inoltre, quando, come nel nostro caso, la radiazione investe solo una parte del corpo, il rischio relativo viene normalizzato al corpo intero per comodità di confronto. A tale scopo sono forniti dei coefficienti specifici per vari organi: per es. quello relativo ai polmoni è 0.12.

La *dose assorbita* corretta sia per l'efficacia biologica relativa della radiazione che per il fattore di rischio specifico dell'organo è indicata come *equivalente di dose efficace*. La sua unità di misura è il sievert (Sv), ed è una grandezza che permette di confrontare danni sanitari diversi e effetti di radiazioni diverse. (In passato sono stati usati il rad e il rem, rispettivamente uguali a 0.01 Gy e 0.01 Sv).

La concentrazione in aria dell'energia alfa potenziale si misura in $J\ h\ m^{-3}$ oppure, facendo riferimento alla corrispondente concentrazione di radon in equilibrio coi suoi discendenti, è indicata in $Bq\ h\ m^{-3}$. La sua unità storica fu coniata per i lavoratori delle miniere ed era il Working Level Month (WLM). Con questa si indicava l'esposizione per 170 ore lavorative in un'ambiente con una concentrazione di 1 WL di figli del radon a vita breve, cioè con un rilascio totale di energia alfa uguale a 1.3 10^5MeV per litro o 1.3 10^8 MeV m^{-3}. Questa è all'incirca l'energia rilasciata dai figli in equilibrio con 3700 Bq (100 pCi) di radon per litro. Essendo 1 $MeV = 1.602\ 10^{-13}\ J$, e il mese lavorativo di 170 ore si ha che 1 $WLM = 3.54\ mJ\ m^{-3}$ e, reciprocamente 1 $mJ\ h\ m^{-3} = 0.282\ WLM$.

Per le considerazioni dosimetriche sarebbe anche necessario tener conto del disequilibrio in termini di energia alfa potenziale che si crea all'interno dell'apparato respiratorio fra la miscela dei discendenti del radon e i loro rispettivi progenitori. Per scopi protezionistici può essere sufficiente usare, a tal fine, un fattore correttivo 0.4. Per quanto concerne il tempo di occupazione degli ambienti si considerano 2000 ore per anno per i lavoratori e 7000 ore annue per gli ambienti domestici.

Si può così stimare che vivere in abitazioni con un tenore di radon di 1 $Bq\ m^{-3}$ comporti un'esposizione di norma uguale a $1.56 \cdot 10^{-2}\ mJ\ h\ m^{-3}$ cioè $4.4 \cdot 10^{-3} WLM$. Mentre la stessa situazione in ambienti di lavoro porta a una esposizione di poco superiore a $10^{-3} WLM$.

Le variabili sono molto più complesse per le considerazioni relative al danno biologico o sanitario sui lavoratori e sulla popolazione in genere; infatti è nota la grande variabilità biologica fra individuo e individuo in risposta agli stessi stimoli. Esistono poi, altre differenze legate all'età, al sesso, alla razza, all' attività, alle abitudini (es. fumo che sembra avere un effetto sinergico col radon).

Non si è ancora certi che il danno sia rapportato linearmente alla causa che lo produce ed, in aggiunta, conosciamo ancora poco sulla cancerogenesi e sui vari sinergismi tra cause diverse. Questi richiami sono utili per sottolineare i limiti delle estrapolazioni dei possibili effetti biologici a lungo termine e delle generalizzazioni a popolazioni di individui in condizioni diverse da quelle osservate. (Nel nostro particolare caso le osservazioni fatte riguardano quasi esclusivamente i minatori).

Esistono però autorevoli organismi scientifici internazionali che, alla luce degli studi più significativi, forniscono indicazioni affidabili ed aggiornate. I dati più recenti, relativi al di rischio di morte per cancerogenesi ai polmoni per esposizione cronica al radon, sono dell'ordine di $8.0 \cdot 10^{-5}$ casi per $mJ\ h\ m^{-3}$, cioè circa $3 \cdot 10^{-4}$ casi per WLM (orientativamente: 1 caso per milione per $Bq\ m^{-3}$).

I sondaggi finora effettuati portano a ritenere che, oggi, la media globale della concentrazione di radon nelle abitazioni sia intorno ai 15 $Bq\ m^{-3}$ con un ampio spettro di variabilità (da pochi $Bq\ m^{-3}$ a $10^5\ Bq\ m^{-3}$ cioè fino ai valori riscontrati agli inizi nelle miniere sotterranee di uranio). Nei casi di concentrazioni eccessivamente alte sono oggi richiesti veri e propri interventi di bonifica.

Nella recente indagine italiana si riporta una media annuale "pesata" di 77 $Bq\ m^{-3}$ e si suppone che il 20% dei tumori polmonari possa essere imputabile al radon [4]. Gli organismi sovranazionali raccomandano controlli finalizzati a garantire che negli ambienti confinati le concentrazioni di radon non superino i 200-600 $Bq\ m^{-3}$ corrispondenti a 3 e 10 mSv si dose efficace all'anno (vedi Tabella B3). A tal fine si suggerisce di fissare una "soglia di attenzione" sui 200 $Bq\ m^{-3}$ e una "soglia di intervento" pari a circa 2 volte la soglia di attenzione.

Nei paesi occidentali sono già in vigore norme uniformate a tali raccomandazioni per cui, particolarmente per le nuove costruzioni, vengono richiesti speciali provvedimenti atti a ridurre la presenza di "radon indoor".

I provvedimenti più semplici possono essere l'impiego di materiali particolari a basso tenore di radio, l'uso di sigillanti a livello del suolo per impedire la penetrazione del radon nei piani sovrastanti, speciali sistemi per il pompaggio dell'aria o più semplicemente il miglioramento del ricambio dell'aria.

Nella Tabella B3 sono calcolate l'esposizione e l'equivalente di dose efficace per i due livelli di concentrazione sopra citati.

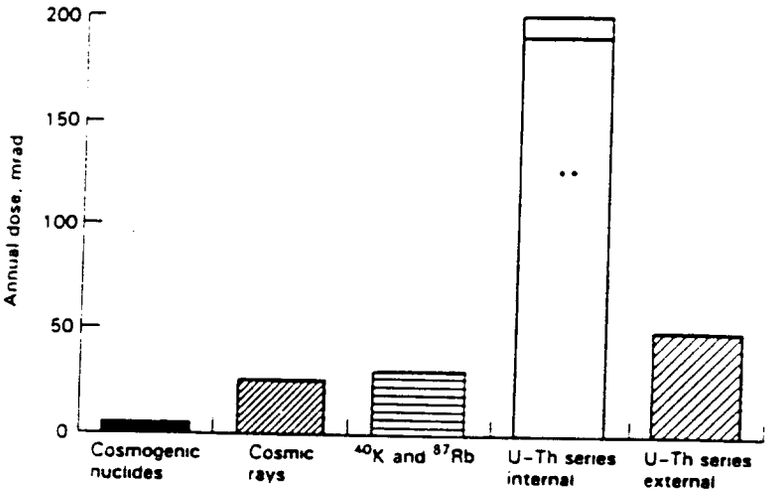
Tabella B3

Annual exposures for action levels of 200 (Bq m^{-3}) and 600 (Bq m^{-3}) in dwellings

Action level (effective dose)	3 (mSv y^{-1})	10 (mSv y^{-1})
Action level (radon concentration)	200 (Bq m^{-3})	600 (Bq m^{-3})
Annual exposure to radon gas	1.4 (MBq h m^{-3})	4.2 (MBq h m^{-3})
Annual exposure to progeny	3.11 (mJ h m^{-3})	9.33 (mJ h m^{-3})
	0.88 WLM	2.63 WLM

La Tabella B4, invece, riporta le dosi medie annue assorbite dagli individui per la presenza dei radionuclidi naturali e della radiazione cosmica. È evidente la grande preponderanza del contributo dell'uranio e del torio per quanto riguarda la dose interna (derivata da radionuclidi che si depositano all'interno del corpo). Di questa il responsabile quasi esclusivo è il radon 222. Tradotta in termini di equivalente di dose efficace la media globale dovuta alle radiazioni naturali è stimata in circa 2.4 mSv all'anno per l'adulto.

Tabella B4



The contribution of each of the components of the natural background exposure is shown, with the dose expressed in millirad per year. The vertical column for the U–Th series internal dose is further subdivided to show the overwhelming contribution of the ^{222}Rn daughters, marked **, to the total internal dose from the U–Th series.

Riferimenti bibliografici

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