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SOME REMARKS ON INDUCED RADIOACTIVITY

by

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G E N E V A

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Some Remarks on Induced Radioactivity

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I. Beam Current Limitation due to Induced Radioactivity

An obstacle to the increase of the intensity in existing synchro-cyclotrons is the radiation field caused by induced radioactivity.

The attached figures show the radiation field both inside the tank and outside the CERN machine, as measured by the CERN Health Physics Group under Dr. J. Baarli, who has kindly permitted my use of the figures.

The field inside the tank is of the order of a few Rem/hour 17 days after shut-down. One day after shut-down, these fields are certainly three times bigger. Clearly there is a limit in beam current for which no human work is possible inside the tank any more. The maximum dose that a person may receive at one time is 3 Rem, and this once a year only. The least figure for the duration of any work inside the tank would be set at about 3 minutes, including time for crawling in and out again. This gives a maximum tolerable radiation field of one Rem per minute, that is 60 Rem/hour, which is five to ten times what we have one day after shut-down, depending upon the location inside the tank.

Clearly all pieces of equipment that need servicing, replacement or repair should be taken out of the machine tank and replaced by items that can be taken out and put back into position again by remote control, if any further increase in the circulating beam is contemplated.

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II. Behaviour of Various Materials with Respect to Activation

Some consideration has been given at CERN to the differences that may exist between materials with respect to activation hazard. The spallation cross-section for production of the most important radioactive isotopes from various materials by protons at cyclotron energies have been measured experimentally at several laboratories and are available. We must also take into account the desintegration scheme. Some radioactive nuclei emit several gamma quanta, others have an electron conversion with a certain probability. Thus the efficiency of the various nuclei in emitting a gamma is different in each case. Furthermore, the number of quanta necessary to produce one Rem depends on the energy of the gamma ray. At last we must consider the absorption of the gamma quantum in the irradiated material itself in the case of voluminous active parts. We have been led thus to define a "danger parameter" which seems characteristic for a given material with respect to the hazard it represents when it is activated up to saturation. This figure of danger we have derived is

$$D = \frac{N}{A} \sum_{\nu\mu} \frac{\sigma_\nu \epsilon_{\nu,\mu}}{k_\mu \chi_\mu} \quad \text{Rem cm}^2,$$

where

$N = 6 \cdot 10^{23}$ is Avogadro's number,

A = the atomic number,

σ_ν = the spallation cross-section for the ν^{th} isotope in cm^2,

$\epsilon_{\nu,\mu}$ = the efficiency of this isotope in emitting a μ^{th} gamma quantum in percent,

k_μ = the number of quanta per cm^2 of the type μ to produce one Rem,

χ_μ = the narrow beam mass absorption coefficient for the μ-type quantum in gr^{-1} cm^2.

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The following table gives the D-values for various materials in units of 10^{-13} Rem cm^2 calculated with the spallation cross-sections available in the literature for protons. Also, in this table, isotopes with life-times less then 24 h. are not considered.

Table I

Material	H	Be	C	O	Al	Fe	Co	Cu	Zn	Ta
D (in 10^{-13} Rem cm^2)	0	3.4	1.8	1	54	66	160	87	153	5

The danger parameter D has a simple physical meaning. If we multiply D by the flux of protons per sec and cm^2 we get the radiation field in Rem/sec in front of a thick wall of uniform activity that has been saturated about one day after end of irradiation.

Various experiments have been conducted at CERN in order to compare the activation of different materials.

A series of small samples have been irradiated by protons for two years now and we are for the first time in a position to give measured data on activated materials with such a long irradiation time. The size of the samples was about 30 x 30 x 5 mm^3. They were irradiated longitudinally. Table II indicated the activity per gram measured three weeks after the end of irradiation, a) with a 3" x 3" NaI (Tl) crystal at a distance of 36 cm and b) with the tissue equivalent ionisation chamber in contact. (The chamber was a Landis & Gyr EQN1, where $80 \cdot 10^{-15}$ Amp is equivalent to one millirad/hour).

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Table VI

Material	a) Counts/gr. min.	b) 10^{-15} Amp/gram
C	500	0.417
Mg	12 700	14.2
Electron	10 650	10.6
Al	4 940	4.95
SiO_2	2 950	3.1
Ti	14 400	27.6
Fe	10 900	16.9
Stainless Steel (17% Cr, 11% Ni, 2% Mo)	15 500	21.8
Cu	9 900	12.4
Co	48 500	114
Zn	15 500	19.4
Ni	35 000	71.5
Mo	15 400	22.5
Pb	1 600	1.71

The samples were located inside the tank, downstream 90° from the target region, 9.5 cm below median plane, at a radius of 2.20 m, which is roughly equal to the target radius.

In a second experiment voluminous cylindrical samples have been irradiated for 8 months in a uniform flux of neutrons of high energy. These samples were located 3 m from the target region of the CERN Synchro-Cyclotron in the forward direction outside the tank. The diameter was 5 cm, the length 2.5 times the 1/2 absorption length for a 1 MeV quantum in the respective materials. Table III gives the measured activities a) at 1.5 m from the NaI (Tl) crystal and b) 6 cm above the tissue equivalent

chamber, 3 weeks after the end of irradiation. A 3 cm diameter lead collimator was used in both cases.

Table III

Material	a) Counts/min.	b) 10^{-15} Amp
Concrete (Ordinary)	865	1.9
Al	1 055	4.5
Fe	10 913	48.5
Cu	7 519	35.5
Zn	12 667	60.5
Pb	401	2.5

The experimental figures quoted in Table II and III cannot be compared directly with those in Table I. It is impossible to measure the danger parameter directly because of the arbitrary exclusion of all activities under one day, and because the irradiation is supposed to have had an infinite duration. However, it can be estimated as soon as the cross-sections are known. In Table II small samples were measured, thus the absorption is absent. Also the Mg, Electron, Al and SiO_2 samples are clearly not saturated, the intensity increasing by a factor 2.6 when saturation is reached. Column a) gives counts in a NaI crystal, the energy response of which is not flat. The column b) is already better in this respect because the current in the ionization chamber is proportional to the Rem-value.

Table III was obtained with thick samples. However, these were activated purely by neutrons, so the results cannot be compared to Table I which was calculated for activation by protons. As the irradiation time was still shorter than in the

preceding case, the materials quoted are also less saturated. The missing factor in the materials mentioned above is here 6.4.

We can, however, draw some general conclusions from these preliminary results. In general they show qualitative agreement with the calculated danger parameter values.

The least dangerous materials are those of atomic number in which Na22 cannot be formed, e.g. C, O, etc.

After these comes the series where Na22 is the most serious hazard : Al, Mg, Si, of which Al is the most favourable. Incidentally Calcium, which was measured in a separate experiment, shows very little Na22 formation. Hence, marble $CaCO_3$ is an absorber with low activity.

Then comes, from Titanium upwards, the series of the usual metals, which give rise to the heavily radiating isotopes of Scandium, Manganese, etc. Here, surprisingly, iron is more radioactive than expected, at all events more than copper. Stainless steel is worse than iron. Nickel and especially Cobalt are still worse. Aluminium, when saturated, should be a little more favourable than Copper, although Mg and Si are not.

Finally come very heavy but non spontaneously radioactive materials, as Ta or Pb, that appear to have a smaller activity. In fact the measurements made on lead 3 weeks after shut-down and reported here are somewhat misleading, because the activity of lead decreases very rapidly whereas that of Fe, Cu does not. Three days after shut-down, the activity of lead was 5 times bigger than reported, which amounted to about 1/8 of the iron activity and 1/5 of the copper activity in counts with the NaI crystal for the thick samples of Table III. Anyhow, lead appears to be promising also as an absorber, if one is prepared to wait several days.

Concluding Remarks

New cyclotrons should be built with distributed absorbers to cover the pole pieces.

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One should, however, be cautious in placing absorbers in the tank of an existing cyclotron. One cannot easily distribute them. Concentrated absorbers in form of clippers can only be placed with ease in free regions outside the dees. They will accumulate the activity in themselves in localized hot spots near the region where access is necessary. In each case a careful calculation of the expected gamma radiation field would be required.

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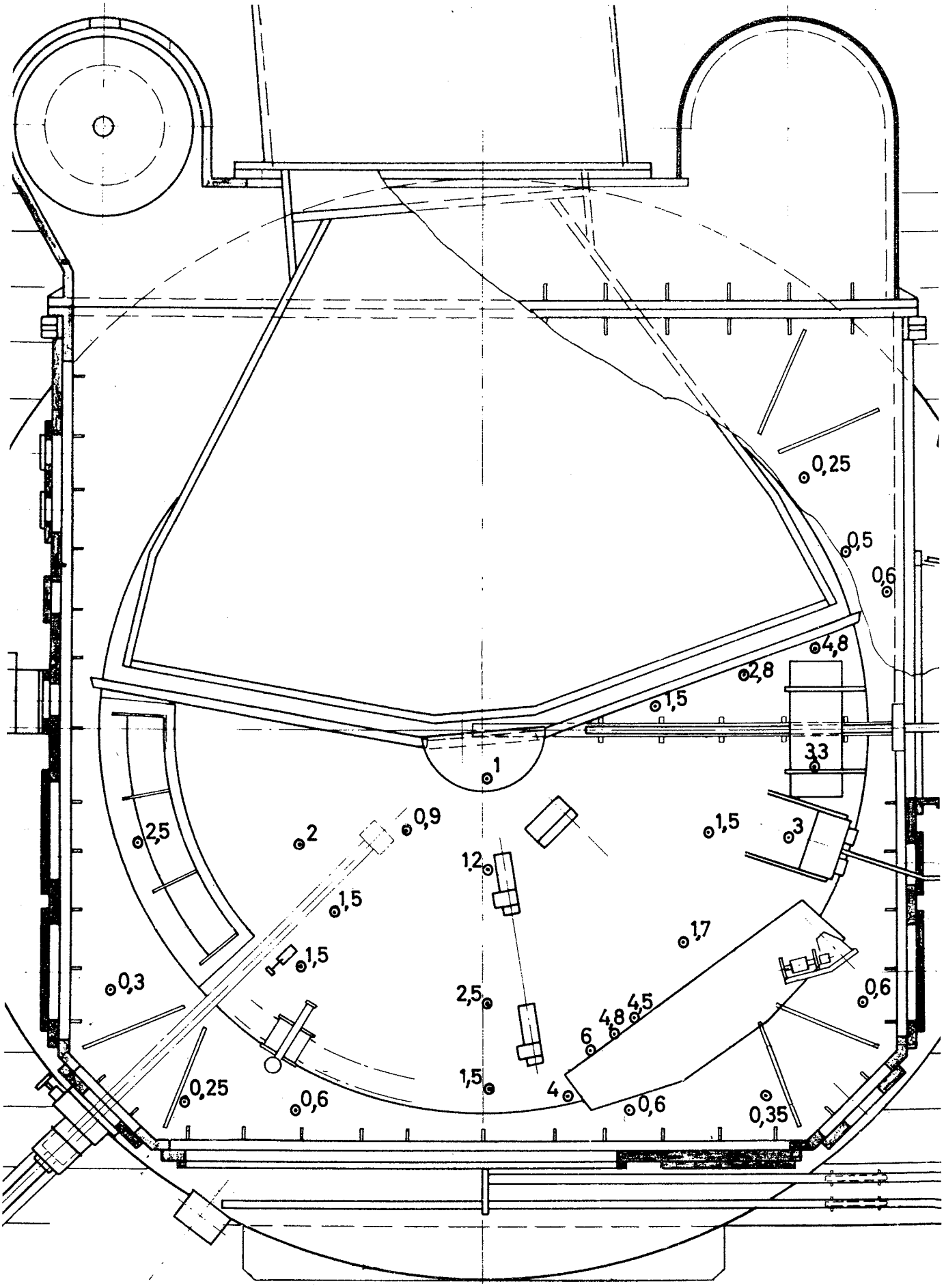
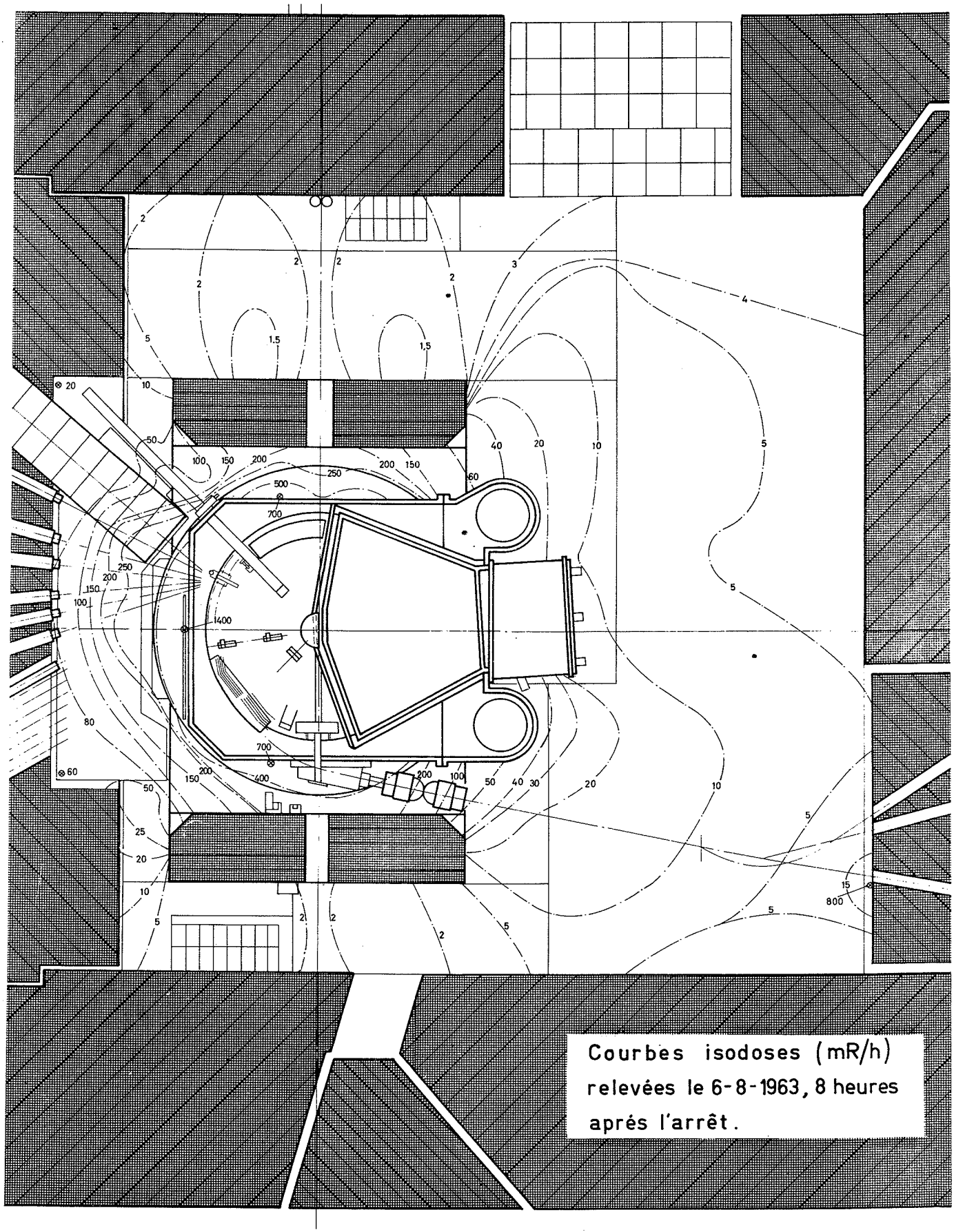


Répartition de la radioactivité à l'intérieur du tank en Rem/h, 17 jours après l'arrêt, le 9-1-1963.


Courbes isodoses (mR/h)
relevées le 6-8-1963, 8 heures
aprés l'arrêt.