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REACTOR ACTIVATION OF CERTAIN SANDS AND CLAYS

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ABSTRACT

The total gamma-ray intensity and the amounts of the principal radioisotopes have been measured between 2 and 100 hours after the end of a short activation of some natural sands and clays.

The dominant radioactivity in alluvial sands of the Linth-Limmat River System (Switzerland) is, between 2 and 20 hours, from manganese-56; and between 20 and 99+ hours, from sodium-24. The atomic densities of sodium and manganese in these sands, as determined by neutron activation, average 4.2×10^{20} and 0.043×10^{20} cm^{-3} respectively. The residual radioactivity 40 days after the end of a 15-min activation is about 0.001 that at 30 hours.

Certain of the mineral grains in the sands were studied separately. The atomic densities of sodium and manganese are reported for dolomite, quartz, sernefite, and serpentine grains. There is a variation by a factor of 40 or more in the induced sodium-24 radioactivity of equal-sized grains of the same mineral fraction. The induced radioactivity drops by a factor of 0.5 when the grain size increases from 0 to 6 mm, and by a factor of 0.8 when the sample size increases from 0 to 6 grams.

A rapid method, based on activation factors, that gives the expected radioactivity in activated sands and clays is presented.

I. INTRODUCTION

Crickmore and Lean [1962 a,b] found that 1 day after the end of a 30-hour activation of fine quartz sand in a reactor, the principal radioactivity was from sodium-24 and from bromine-82. They used this radioactive sand to study the transport rate of sand in the bed of a 105-meter flume. Their work suggested the possibility of using activated natural sands and clays for various other short-term laboratory studies in hydraulics research.

A prerequisite for such studies is knowledge of the radiological properties of the sands and clays that are to be used. Two such properties have been measured between 2 and 100 hours after the end of a short activation of some natural sands and clays: the total γ-ray intensity, and the amounts of the principal radioisotopes. These data are presented here, together with a rapid method for predicting the radioactivity in rocks and minerals that are to be activated.

II. MATERIALS AND METHODS

A. Description of the Sand and Clay

Two types of sand were studied. The first (A) was a limestone type found close to the Limmat River near Dietikon. The mineral content of this sand may be seen in Table I. The second (B) was also a limestone type that is found close to the upper lake of Zürich near Nuolen. Both are sands used in sediment transport studies, both are from ordinary gravel pits, and both have the same geological origin. Grains of certain minerals were separated from the sand; these were studied as well as samples of mixed sand. The two clay samples were dry powders of sodium bentonite from Ponza, Italy (GEL 220 mesh) and of opalinus-clay (illite type).

B. The Activations

The activations took place in the thermal column, at a pile factor of 30, of the Diorit reactor at Würenlingen, Switzerland. Most activations were for 15 minutes, but a few were longer, and one was of 21.3-hour duration. The sample size was 5 g or less. During the activation, each sample was sealed inside a thin polyethylene wrapper.

C. The Detection Instruments

The instruments used in this study were manufactured by Landis und Gyr A. G., Zug, Switzerland. The γ-ray intensity was measured with a shielded Geiger-Müller tube that was mounted in a portable ratemeter, type EMD 1.2. Other measurements were made with halogen-quenched G-M tubes, type EQH. 3, that were powered by high-voltage supply ratemeter type EMA. 1.

III. RESULTS

A. Radiological Measurements

The γ-ray radioactivity in all the samples that were studied was from sodium-24 and from manganese-56 in the period 2 hours to 70+ hours after the end of the activation. The γ-ray intensity fell with the 15.0-hour half-life of sodium-24 between 40 and 70+ hours in all samples, and between 17 and 70+ hours in the two samples of mixed sand.

The γ-ray intensities are given as measured in Table II. The intensities listed for Mn^{56} were obtained by subtraction of the extrapolated Na^{24} intensity at t = 2 hours from the total measured intensity.

The effects of particle grain size and total sample size on measured γ-ray intensity were measured. The results are presented in Fig. 1. By use of Fig. 1, the complete γ-ray intensity decay curves have been prepared

for 5-gram samples of fine grains that passed through a sieve with a mesh of 0.01 mm, henceforth called the 0.00 fraction. These are presented in Fig. 2. By use of the appropriate gamma-ray dose-rate constants [G. J. Hine and G. L. Brownell, eds., 1956] and also Figs. 1 and 2, the absolute induced radioactivity and the atomic density of sodium and manganese in the samples have been computed. The method is described in Appendix II, and the values are given in Table III.

B. Other Measurements

1. Washing

In order to test for the degree of binding of the radioactive sodium on the sand fractions, all the samples of mixed sand A were separately washed by 2.5 hours of agitation in 100 ml of distilled water. There was no reduction in γ-ray intensity other than that from the decay of sodium-24. Five percent of the intensity of the 0.00-mm fraction remained in milky-brown suspension in the wash water. Otherwise, none of the wash water contained radio-activity that exceeded 0.5% of that in the sample.

2. Investigation of Individual Grains

The 2.97-, 4.00-, and 5.32-mm fractions of mixed sand A were studied grain by grain four days after the end of the activation. The serpentine and sernefite stones were stronger emitters of γ-rays than the rest, by a factor of about 3.

Six individual 0.33-mm grains of serpentine and eight of sernefite were examined one by one 30 hours after the end of a 21-hour activation at pile factor 26. The results are given in Table IV. The grains vary in size from 0.2 to 0.5 mm. This helps to explain the great variability in radioactivity,

but the largest grain was activated only 1/4 as much as some smaller grains, and some grains had either zero or an exceedingly small amount of activity.

3. Evidence of Residual Radioactivity

Forty days after activation, fractions 4.00 and 5.35 of mixed sand A, and opalinus clay, were measured for radioactivity. A residual radioactivity that amounted to about 0.001 of that at 30 hours was detected in these samples. The residual activity was found to lie between 0.05 and 0.2 mr/h when each of 24 stones of fraction 4.00 was placed on the protective screen immediately above the Mylar end window of a G-M counting tube. The 25th stone in this sample read 0.4 mr/h. The individual stones of fraction 5.35 were also examined in this manner. Ten stones read between 0.1 and 0.2 mr/h, and the final stone read 2.2 mr/h, that is, about 1.5 times the sum of the others.

IV. DISCUSSION

A. Decay Curves and Radioactivity of Sand and Clay

The atomic densities of sodium and manganese that are derived from the decay curves of induced radioactivity in the sand and clay samples are consistent with published values. The radioactivity that is expected when average igneous and sedimentary rock and limestone are activated in a reactor has been computed by The Activation Factor Method and is presented in Appendix I.

The avarage atomic densities of sodium in Swiss granites and dolomites are 7.8×10^{20} and 1.4 max $\times 10^{20}$ [Niggli, et al., 1930]. In sedimentary rock it is 2.2×10^{20} [Hodgman, et al., eds., 1958]. Our values for mixed sand, serpentine, and sernefite lie between these; for dolomite our value is less than the 1.4 maximum by a factor of 3.5. Our value for quartz is about 5 times the value of Crickmore and Lean that was estimated from

their figure of 10 μCi/g, 24 hours after a 30-hour activation at pile factor 10. Therefore, our mixed-sand samples contained about 150 times as much sodium as did the carefully selected quartz fractions used by these authors. That they found Br^{82} radioactivity and we did not can be explained by the overwhelming Na^{24} activity in our samples that dominated the decay curve between 20 and at least 100 hours.

Niggli et al. [1930] give the value of 7.6×10^{18} for the atomic density of manganese in Swiss granites. Our values range from 2.3×10^{18} in quartz to 8.7×10^{18} in serpentine. The 2.6-hour half-life of Mn^{56} dominated the γ-ray decay curves of our samples between 2 and 20 hours. The effect on the decay curve when the Mn density remains constant and the Na density drops by a factor of 30 may be seen in comparing the mixed sand and quartz fractions in Fig. 2.

B. Effect of Particle Size and Sample Size

The progressive drop of per-gram γ-ray intensity with increasing sample size may be explained by self-absorption of the rays. However, the independent drop in per-gram intensity with increasing particle size requires another explanation. The macroscopic cross sections for the important induced radioisotopes Na^{24}, Al^{28}, and Mn^{56} amount in sum to no more than 10^{-4} per mm in igneous rock. Thus local depression of the neutron flux with depth into the stones is negligible. It is possible that the bulk of the sodium in these samples is strongly fixed to the surface of the sand grains.

C. Variation in Individual Grains

The variation in radioactivity induced in individual grains of equal size amounts to a factor of 40 or more. This finding also indicates that the sodium atoms are not evenly distributed in the mineral grains. This

strong and unpredictable variation between grains of equal size will limit the usefulness of natural sands as activated tracers in hydraulics research. If uniformly activated grains are required, then the grains must be selected one by one or in small groups after activation.

D. Residual Radioactivity

The amount of residual radioactivity in the mixed sands was so low that it is unlikely that it will be a problem during a series of laboratory experiments. The half-life of the residual radioactivity probably is between 1 and 5 weeks. Although the phosphorus density in dolomite sands is unknown, it is possible that it approaches 2×10^{19} at/g, the amount in Swiss granites [Niggli, et al., 1930]. If so, the residual radioactivity that will be present at the level of 20 nCi/g 40 days after activation may be phosphorus-32. The great variation in residual radioactivity between grains of similar size and appearance reveals a great difference in density of the activated elements.

V. SUMMARY AND CONSLUSIONS

The principal radioactivity in natural alluvial sands of Switzerland that have been activated for short periods in a reactor is from manganese-56 (between 2 and 20 hours), and from sodium-24 (between 20 and 99+ hours).

The atomic densities of sodium and manganese in these sands average 4.2×10^{20} and 0.043×10^{20} cm^{-3} respectively. The atomic density of sodium is also reported for opalinus and sodium bentonite clays, and of sodium and manganese for dolomite, quartz, sernefite, and serpentine.

There is a variation by a factor of 40 or more in the induced sodium-24 radioactivity of equal-sized grains of the same mineral fraction. The induced radioactivity of samples drops by a factor of 0.5 when the particle size goes from 0.00 to 6 mm, and by a factor of 0.8 when the sample size increases from 0.00 to 6 grams.

No more than 0.5% of the induced sodium-24 activity is removed from the sand grains by washing them for 2-1/2 hours in water.

The strong radioactivity of sodium-24 in activated natural dolomite sands makes them potentially very useful tracers for short-term field or laboratory research. The residual radioactivity 40 days after the end of a short activation of these sands is about 0.001 of that at 30 hours. Therefore the problem of residual contamination will be negligible in most applications. When uniform activation of single grains is required, the grains must be selected one by one or in small groups after activation.

A rapid method, based on Activation Factors, that gives the expected radioactivity in activated sands and clays is presented.

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List of Symbols

γ, β, λ, σ, τ	The Greek letters gamma, beta, lambda, sigma, tau
Ci	curies: 1 curie = 3.7×10^{10} disintegrations/sec
mCi, μCi, nCi	milli-, micro-, nanocuries
$T_{1/2}$	half-life
τ	mean life = $(T_{1/2})/0.693$
λ	decay constant $1/\tau$
t	time after end of activation
t_r	activation time in reactor
n^{th}	thermal neutron intensity in neutrons/cm^2-sec
"$n\nu t$"	$n^{th} \times t_r$
r, mr	roentgen, milliroentgen
A	conversion factor = 2.7×10^{-5} μCi per dis/sec
C_1	number of atoms of element 1 per gram of sand or clay
f_i	the fractional natural abundance of isotope i in element 1, e.g. 0.505 of the atoms in the element bromine are from the isotope Br^{79}
σ_i^{act}	thermal neutron activation cross section of radioisotope i, in units of 10^{-24} cm^2/atom
pile factor of 1, 10, 30	reactor thermal neutron intensity corresponding to 1, 10, and 30×10^{11} neutrons/cm^2 sec^{-1}
$N_i(0)$	number of atoms of radioisotope i at the end of the reactor irradiation

APPENDIX

I. Activation-Factor Method for Estimation of Reactor-Induced Radioactivity of Sand Samples

The nuclear reaction of importance in the thermal column of a reactor is the capture of a thermal neutron, e.g., $Na^{23} + n = Na^{24} + \gamma$. This is written normally in the shorthand form $Na^{23}(n, \gamma)Na^{24}$, and is called an n, γ reaction: a neutron is taken into the nucleus with the immediate emission of a γ ray. The resulting nucleus (in this example Na^{24}) may be unstable and have a probability for radioactive decay that is equal to λ, the decay constant. This constant is related to the mean life and the half-life of the radioisotope by

$$\lambda = 1/\tau = \ln 2/T_{1/2} = 0.69/T_{1/2} . \tag{1}$$

The radioactivity of a given radioisotope i is given by

$$N_i \lambda_i , \tag{2}$$

where

$$N_i = N_i(t) = N_i(0)\, e^{-t/\tau} \tag{3}$$

is the number of atoms present at time t after the end of the reactor irradiation.

The dynamic equation for the buildup of an isotope in a reactor is

$$\frac{dN_i}{dt} = k - \lambda_i N_i , \tag{4}$$

where k is the rate of the n, γ reaction, and $\lambda_i N_i$ is the instantaneous decay rate of those atoms already formed. The rate k may be computed from

$$k = C_i \sigma_i^{act} f_i n^{th} , \tag{5}$$

where C_i is the number of atoms of element i (per gram of mineral), σ_i^{act} is the thermal neutron activation cross section for isotope i in

units of barns (cm^2/atom $\times 10^{-24}$), f_i is the fraction natural abundance of isotope i in element 1, n^{th} is the thermal neutron flux in the reactor. Equation (4) reveals that the buildup of a radioisotope N_i (or of its radioactivity $N_i\lambda_i$) follows the curve in Fig. 3. It can be seen that at approximately 2τ the radioactivity reaches a maximum. The sample is then said to be saturated. It can also be seen that early, when $t_r \ll \tau$, the buildup is linear with time, i.e., it follows curve (a) in the figure.

The activation-factor method for estimation of radioactivity uses these facts: when $t_r \ll \tau$, the activation factor is linear with t_r, and when $t_r \gg \tau$, the activation factor is independent of t_r:

$$\text{Activation Factor} = \sigma_i^{act} f_i n^{th} t_r \lambda_i A \qquad (\text{for } t_r \ll \tau), \qquad (6)$$

$$\text{Saturation Activation Factor} = \sigma_i^{act} f_i n^{th} A \quad (\text{for } t_r \gg \tau). \qquad (7)$$

Only when $t_r \approx \tau$ is this method in serious error: in this case both factors give a value 31% too high (see Fig. 3). Table V gives activation factors for the chemical elements of interest in sand and clay activations.

In order to use these activation factors C_1, the number of atoms per gram of sand or clay of the element in question must be known. The product of C_1 and the suitable activation factor gives directly the number of microcuries of radioisotope at the end of the reactor irradiation.

An example of the use of this method is given in Table VI-A, B, C, in which the expected radioactivity per gram at $t = 0$ (after 15 minutes of reactor irradiation at pile factor 30) is given for average-composition igneous and sedimentary rock and for limestone. It may be seen that at $t = 0$ the greatest radioactivity expected is in every case from Al^{28} with a 2.3-min half-life, but that between 10 hours and 10 days it is from Na^{24}. It should

be cautioned that this Table is incomplete because the C_1 for certain elements, notably P and Mn, are not at hand. There is experimental evidence that phosphorus and manganese radioisotopes may be important in reactor-activated sands.

II. Conversion of Measured Gamma-Ray Intensity to the Amount of Radioisotope, and to the Amount of the Chemical Element in the Sample

The two principal γ emitters in this work are Mn^{56} and Na^{24}; their half-lives are respectively 2.6 and 15 hours. When the fraction of the γ radiation from a sand or clay sample that decays with one of these half-lives is established by measurement, then the number of microcuries of this radioisotope that remains in the sample can be estimated by use of the suitable γ-ray dose rate constants [G. J. Hine and G. L. Brownell, eds., 1956]. Converted to milliroentgens per hour at 20 cm and to μCi, these constants are

$$\mu\text{Ci} = 44 \text{ (mr/h at 20 cm) for } Mn^{56}$$

$$\text{and } \mu\text{Ci} = 21.5 \text{ (mr/h at 20 cm) for } Na^{24}.$$

The simplest case is when essentially all the γ radiation is decaying with, say, the sodium-24 half-life. Then, the meter reading at 20 cm distance of a hand instrument in mr/h, corrected by use of Fig. 1 to 0.00 g sample size and to 0.00 mm grain size, may be multiplied by 21.5 to give the number of microcuries of Na^{24} in the sample.

The number of atoms of sodium and manganese in the sample may easily by found after the number of μCi of Na^{24} and Mn^{56} has been determined.

The number of μCi at $t = 0$ (at the end of the reactor irradiation) must be found by a simple calculation. The number of atoms of the element in question in the sample is the number of μCi at $t = 0$ divided by the activation factor.

For example, suppose that 60 h after the end of a 15-min activation at pile factor 30, a sample was observed to decay with the 15-h half-life of Na^{24}. The sample emitted radiation that, after correction for grain size and sample size (Fig. 1), measured 0.40 mr/h at 20 cm. Therefore $21.5 \times 0.40 = 8.6$ μCi of Na^{24} remain. Sixteen times this amount, or 138 μCi, was present four half-lives earlier at $t = 0$. The number of atoms of sodium in the sample is 138 divided by the activation factor 5.0×10^{-19} (Table V), or 2.8×10^{20} atoms.

Table I. Distribution of mineral types in sand A.

Size-fraction (mm)	5.35	4.00	2.97	1.46
Number of stones	11	25	69	527
Limestone	82%	64%	64%	47%
Sernefite	—	—	7%	13%
Serpentine	—	—	2%	10%
Quartzite	—	—	1%	—
Sandstone	—	4%	6%	17%
Quartz	—	8%	2%	10%
Granite/Greiss	9%	12%	4%	—
Unknown	9%	12%	14%	3%
	100%	100%	100%	100%

Table II. Radioactivity induced in certain sands and clays.[a]

Fraction	Sample weight (g)	Mean grain size (mm)	Mean grain weight (mg)	Gamma-ray Intensity[b]	
				Na^{24}(mr/h-g)	Mn^{56}(mr/h-g)
Opalinus clay	5.0	0.00	–	2.7	?
Sodium bentonite	5.0	0.00	–	21.6	?
Mixed Sand A	5.0	0.00	–	7.6	(4.0) est.
Mixed Sand A	5.0	0.52	0.65	7.0	(3.7) est.
Mixed Sand A	5.2	1.46	14	5.9	(3.1) est.
Mixed Sand A	5.0	2.97	130	4.9	(2.6) est.
Mixed Sand A	5.0	4.00	320	6.1	(2.3) est.
Mixed Sand A	5.2	5.35	750	4.0	(2.1) est.
Mixed Sand B	1.07	1.1	6.0	7.3	3.7
Mixed Sand B	5.0	0.75	2.0	5.8	(3.0) est.
Mixed Sand B	5.0	0.33	0.18	5.9	(3.0) est.
Dolomite	1.8	7.5	1800	0.35	1.0
Dolomite	0.58	1.1	6.0	0.61	1.7
Quartz	0.10	1.65	21	0.23	3.6
Sernefite	0.64	1.1	6.0	12.5	2.5
Sernefite	0.0093	0.33	0.18	15.0	(3.0) est.
Serpentine	0.14	1.1	6.0	12.0	6.8
Serpentine	0.0093	0.33	0.18	16.5	(9.3) est.

a. From a 15-minute activation at pile factor 30 in the Diorit reactor.

b. Measured at 2.0 hours after the end of the activation and at a distance of 20 cm from the sample.

Table III. Irradiation parameters in certain sands and clays.

Fraction	Radioactivity[a,b]		Atomic Density	
	Na^{24} (μCi/g)	Mn^{56} (μCi/g)	Na (at/g × 10^{-20})	Mn (at/g × 10^{-18})
Opalinus clay	80	?	1.6	?
Sodium bentonite	630	?	12.5	?
Mixed Sand A	220	(340) est.	4.4	(4.5) est.
Mixed Sand B	200	(310) est.	4.0	(4.1) est.
Dolomite	20	165	0.39	2.3
Quartz	7.1	340	0.14	4.7
Sernefite	370	240	7.4	3.3
Serpentine	350	620	7.0	8.7

a. From a 15-minute activation at pile factor 30 in the Diorit reactor.

b. Corrected to the time at the end of the activation. The values are corrected to "0" g sample size and "0" mm grain size, by use of Fig. 1.

Table IV. Activation of individual grains.

Grain number	Serpentine (mr/h at 5 cm)	Sernefite (mr/h at 5 cm)
1	0.8	1.8
2	0.00	0.23
3	1.0	0.09
4	0.7	0.27
5	0.45[a]	0.42
6	1.15	1.8
7		0.42
8		0.05
Average; standard deviation	0.7 ± 0.4	0.63 ± 0.70

a. The largest grain.

Table V. Activation factors.

Radioisotope	Radiation energy (MeV) Beta	Gamma	Half-life	Activation factor[a] for 15 min	Saturation activation factor[a] for $t_r > \tau$	τ
Na^{24}	1.4	1.4	15 h	5.0×10^{-19}	4.4×10^{-17}	21.5 h
		2.8				
Mg^{27}	1.8	0.85	9.5 min	–	2.5×10^{-19}	13.6 min
Al^{28}	2.9	1.9	2.3 min	–	1.7×10^{-17}	3.3 min
Si^{31}	1.5	none	2.6 h	1.8×10^{-20}	2.8×10^{-19}	3.7 h
P^{32}	1.7	none	14.3 days	7.8×10^{-21}	–	–
Cl^{38}	4.8	2.2	37.3 min	3.1×10^{-18}	1.1×10^{-17}	53 min
K^{42}	3.6	1.5 (18%)[b]	12.5 h	8.5×10^{-20}	6.1×10^{-18}	18 h
Ca^{49}	1.9	3.1	8.9 min	–	1.7×10^{-19}	13 min
Ti^{51}	1.5	0.32	5.8 min	–	6.1×10^{-19}	8.3 min
Mn^{56}	2.8	1.2[c]	2.6 h	7.1×10^{-17}	1.1×10^{-15}	3.7 h
Fe^{59}	0.46	1.2	45.1 days	4.1×10^{-23}	–	–
Co^{60}	0.31	1.2	5.3 y	6.0×10^{-21}	–	–
Br^{80}	2.0	0.08	4.4 h	4.3×10^{-18}	1.2×10^{-16}	6.3 h
Br^{82}	0.44	0.77[c]	35.7 h	6.0×10^{-19}	1.2×10^{-16}	51 h

a. Pile factor of 30.

b. Only a small % of disintegrations give off a γ ray.

c. Average energy.

Table VI-A. Expected radioactivity from elements in the various rock types.

	Igneous rock					
		Radioactivity (μCi/g) at				
Element	C_1[a]	t = 0[b]	t = 30 min	t = 10 h	t = 50 h	t = 200 h
Na	7.8×10^{20}	390	380	240	39	4
Mg	4.5×10^{20}	120	14	–	–	–
Al	1.8×10^{21}	30 000	3.5	–	–	–
Si	6×10^{21}	110	100	8	–	–
P	2×10^{19}	0.16			0.14	0.10
K	4×10^{20}	35	33	20	2.0	0.12
Ca	5×10^{20}	80	8	–	–	–
Ti	6×10^{19}	36	1.0	–	–	–
Mn	7.6×10^{18}	540	470	39	–	–
Fe	2.2×10^{20}	0.01				0.01
Br^{80}	1×10^{18}	4.0	4	0.8	–	–
Br^{82}	1×10^{18}	0.6	0.6	0.5	0.2	0.01
Total radioactivity per gram at given t		31 mCi	1.0 mCi	310 μCi	41 μCi	4.2 μCi

a. Average values.

b. $C_1 \times$ Activation Factor for 15 min at pile factor 30.

Table VI-B. Expected radioactivity from elements in the various rock types.

	Sedimentary rock				
		Radioactivity (μCi/g) at			
Element	C_1 [a]	t = 0 [b]	t = 30 min	t = 10 h	t = 200 h
Na	2.2×10^{20}	110	105	70	1.1
Mg	3.4×10^{20}	91	11	—	—
Al	1.6×10^{21}	26 000	3	—	—
Si	6×10^{21}	110	100	8	—
P	?				
K	3.6×10^{20}	31	30	18	0.1
Ca	7.0×10^{20}	110	11	—	—
Ti	?				
Mn	?				
Fe	?				
Br	?				
Total radioactivity per gram at given t		26 mCi	260 μCi	96 μCi	1.2 μCi

a. Average values.

b. $C_1 \times$ Activation Factor for 15 min at pile factor 30.

Table VI-C. Expected radioactivity from elements in the various rock types.

	Limestone				
		Radioactivity (μCi/g) at			
Element	C_1 [a]	t = 0 [b]	t = 30 min	t = 10 h	t = 200 h
Na	1.0×10^{19}	5.1	4.9	3.1	0.52
Mg	1.0×10^{21}	270	31	—	—
Al	9.6×10^{19}	1600	0.2	—	—
Si	5×10^{20}	10	9	0.8	—
P	?				
K	4×10^{19}	3.5	3.3	2.0	0.01
Ca	5×10^{21}	800	80	—	—
Ti	?				
Mn	2×10^{18}	140	125	10	—
Fe	?				
Br	?				
Total radioactivity per gram at given t		2.9 mCi	265 μCi	16 μCi	0.5 μCi

a. Average values.

b. $C_1 \times$ Activation Factor for 15 min at pile factor 30.

FIGURE LEGENDS

Fig. 1. Effect of sample size and particle size on Na^{24} γ-ray intensity.

Fig. 2. γ-Ray intensity decay.

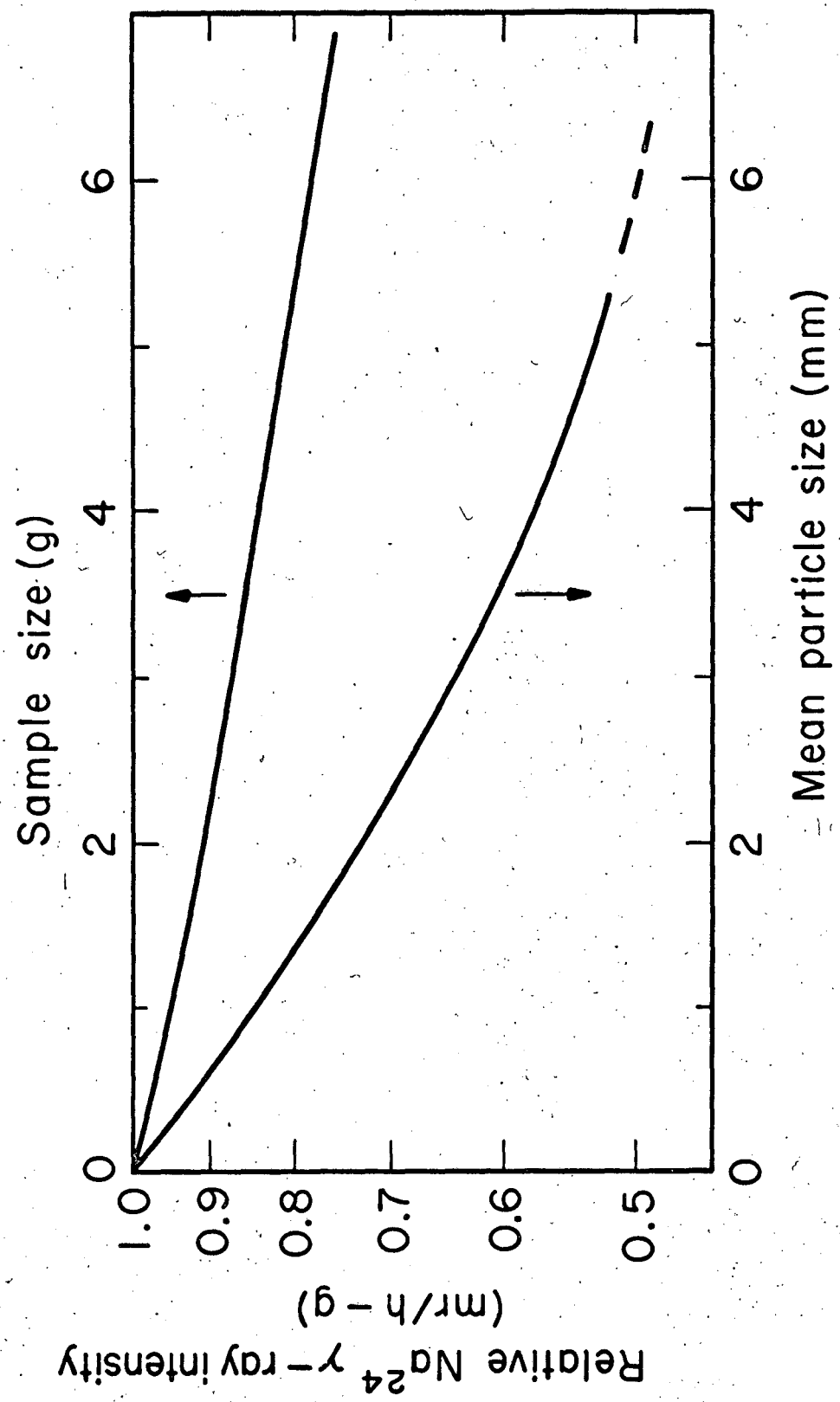
Adjusted to 5.0-g sample size and 0.00-mm grain size. Two to 70+ hours after the end of a 15-minute activation at pile factor 30.

1. Sodium bentonite clay
2. Sernefite
3. Serpentine
4. Mixed sand A
5. Mixed sand B
6. Opalinus clay
7. Dolomite
8. Quartz

Fig. 3. Buildup of radioisotope atoms N_i in a reactor.

a = equation of $\frac{dN_i}{dt_r} = k$,

b = equation of $\frac{dN_i}{dt_r} = k - \lambda_i N_i$.



MU-33633

Fig. 1.

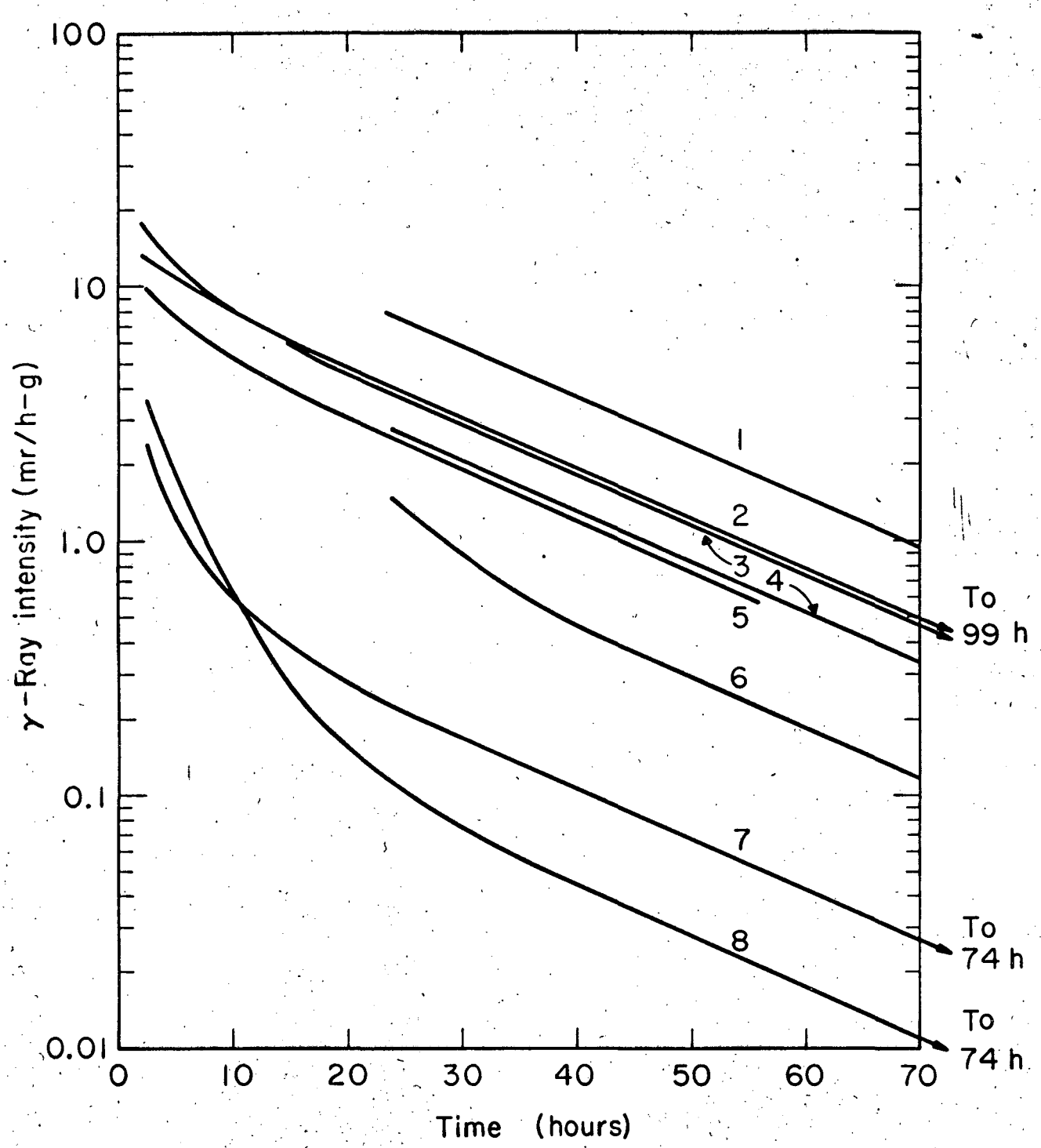


Fig. 2.

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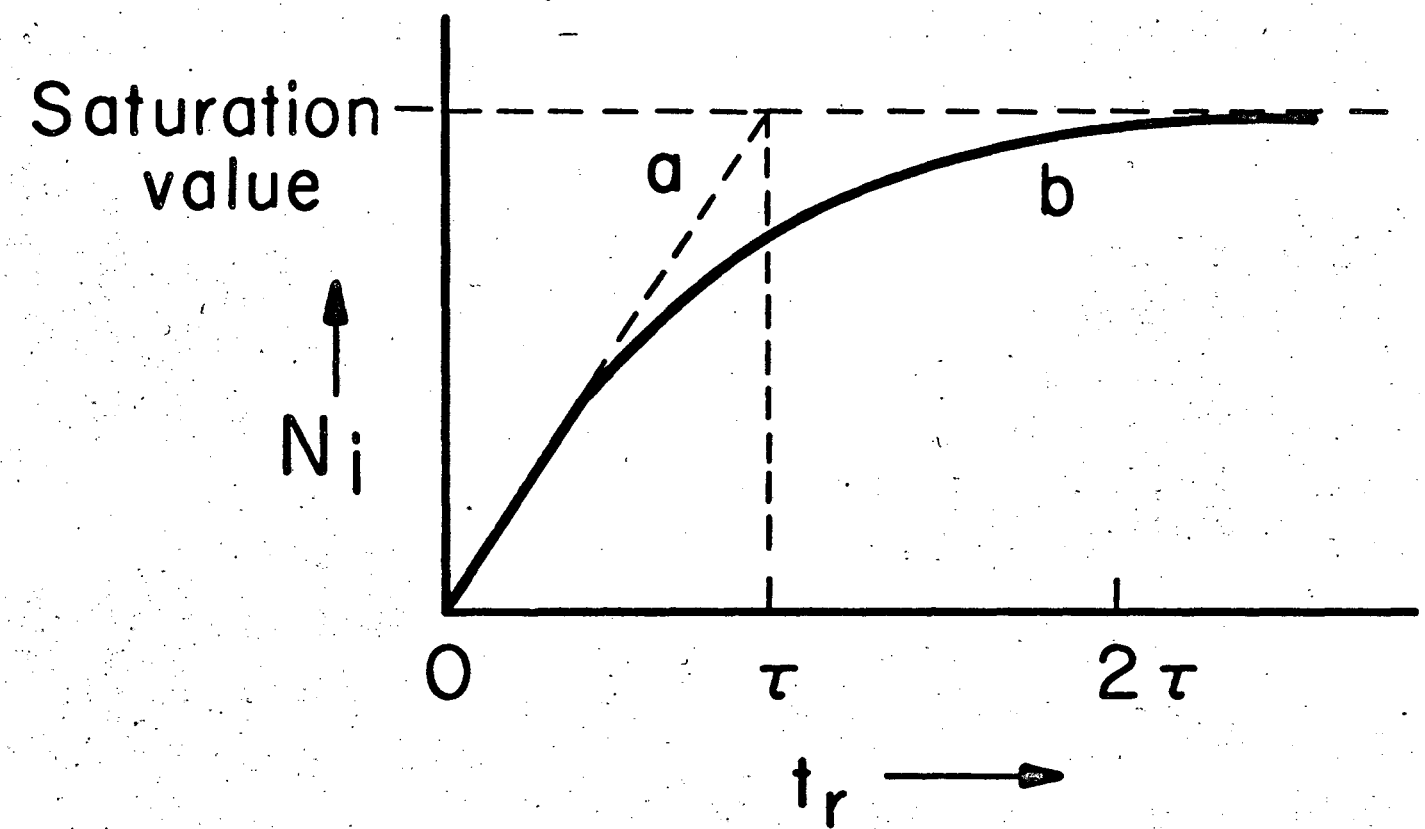

Fig. 3.

MU-33634

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