CR-114173
code-none
pages-31

NSG-232
Columbia University

# Autoradiography: Uncommon Uses

(for publication in Science)

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N70-77774

Abstract: Autoradiography is a process used in making photographs of naturally radioactive materials by using the alpha radiation they emit. It has also been used in tracer isotope studies. Many elements can be made radioactive by neutron irradiation. This paper describes the use of autoradiography in making photographs of materials that have been artificially activated in a nuclear reactor, and emit beta radiation during decay. Most natural materials are nonhomogeneous, and differences in composition can be shown by neutron-activation autoradiography, even when more than one element has been activated. A table is given that can be used to help decide if a particular element will be useful in neutron-activation autoradiography. We found by calculation and by experiment that the method would be useful in the study of thin sections of a large variety of rocks. The most useful common rock-forming elements are Al and Na but accessory elements can often be used, too, if local concentrations are high enough, as in ores. The method can also be used in living organic systems, for example in plant and animal experiments, where it is undesirable or not feasible to introduce radioactive tracers into the system. The element to be studied can be introduced normally, and a specimen such as a bone section can be irradiated later, then studied by autoradiography to learn in what sites the introduced elements may have concentrated.

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# Uncommon Uses

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Autoradiography is a process in which an object containing radioactive material is photographed by using the radiation it emits. Among the first uses of autoradiography was the study of the distribution of uranium and thorium compounds in ores (1-4). Decaying uranium emits alpha particles, so if a photographic film is held next to a cut face of uranium-bearing ore the alpha particles emitted from the flat face, and from a thin zone in back of it, expose the photographic emulsion to give a picture of the distribution of uranium across the face as a function of its concentration.

In the period just after the Second World War radioactive tracers became readily available and came into general use in medicine and biology. In these studies isotopes with short half-lives were introduced into living organisms, and their distribution by physiological processes was studied by monitoring the progress of their beta and gamma radiation through the organism (5). By these means it could be shown, for example, that in human subjects iodine concentrates in the thyroid (6), and phosphorus in the bones, in zones of calcifying cartilage, and in teeth (7). These tracer experiments can also be recorded by scintillation equipment which is sensitive exclusively to gamma radiation (8). In laboratory animals, where longer-lived isotopes and/or larger quantities of radioactive tracer have been used, organs and tissues have been studied in the living animal with scintillation equipment, and with autoradiography after the animal has been sacrificed.

Autoradiography using tracers has been accomplished at the electron-microscopic level (9), and structural studies of

chromosomes have been carried out by examination of autoradiographs with an optical microscope (10).

To date, therefore, most autoradiographic work has been done using radioisotopes as tracers, and has been employed in biological, physiological, and medical research. This introduction will be quite familiar to workers in those fields. Some work, however, has been done in alloy systems: for example $Cr^{51}$, $Mn^{54}$, and $Cu^{64}$ have been used as tracers in an Al-Zn-Mg alloy to study their relation to metallographic structures before and after hot-pressing and annealing (11). Self-diffusion of Au in Au and in Au-Ni alloys has also been studied by use of radioactive gold tracers (12, 13).

Neutron Activation Autoradiography

There is another potential application of autoradiography that is very simple in concept. This involves activating a normally nonradioactive material with thermal neutrons so that it will give an autoradiograph. Our literature search has turned up only a few isolated examples. In important early work minerals containing Mn, Au, Cu, W, P, K, Ba, Na, and As have been investigated, using stray neutrons from a cyclotron as a source of radiation (14, 15). Autoradiographs of neutron-activated ores containing these elements were successful. A microperthite and an Al-Cu alloy have been activated (16); Na in the microperthite and Cu in the alloy appeared on the autoradiograph with microscopic resolution.

$B^{11}$ undergoes a thermal-neutron reaction to $B^{12}$, which has the very short half-life of .022 seconds. Steel samples

containing boron have been irradiated in a nuclear reactor with photographic film in contact with one surface. A combination of alpha and beta radiation from decaying $B^{12}$ makes an autoradiograph which is apparently not clouded too much by the flux during irradiation (17). Recently the method of neutron activation autoradiography has been used to copy old photographs of historic interest that have faded badly (18). The old photograph, which contains $Ag^{107}$ in its image, is irradiated in a reactor to produce the radioactive daughter, $Ag^{108}$, with a half-life of 2.3 minutes. The activated photograph is then used to expose a negative, and the resulting print shows an image that is greatly enhanced over the original.

Autoradiography by thermal neutron irradiation can be particularly valuable if used in conjunction with neutron activation analysis. The examples just cited indicate that there are many useful applications, and we find it noteworthy that the method is not in general use. In the balance of this paper we describe the process and discuss possible applications.

## Feasibility of the Method

The method takes advantage of the facts that 1. a very large number of naturally occurring isotopes will undergo nuclear reactions in a neutron flux to produce radioactive daughter nuclides, and 2. no natural or artificial material is completely homogeneous. In those materials whose inhomogeneities are on a larger scale than microscopic, it is probable that neutron activation followed by

autoradiography will display some aspect of its nonhomogeneous nature in a photograph; for microscopic inhomogeneities good possibilities exist also.

A few examples of materials that can be studied by neutron-activation autoradiography are thin sections of rocks, metallographic thin sections and metal foils, bone thin sections, and organic tissue. The minerals in rock have differing concentrations of elements that can be activated, and autoradiographic studies can use these. In artificial materials such as commercial glasses, experimental petrology samples, and metallic alloys, the concentrations of appropriate elements in the bulk sample can be controlled and their distribution in the final product studied, without the necessity of introducing radioactive tracers into the starting materials. This can also be done in living organic systems.

Problems encountered in the method involve interference of nuclide activities in an autoradiographic image (the question of which nuclide produced what part of a given exposure), resolution of fine detail in the image, and the exposure-threshold properties of photographic emulsions.

In many cases more than one element in a sample can be made highly active by irradiation. These will not interfere with each other on the autoradiographs if their half-lives are sufficiently different so that irradiation and decay times and film exposure times can be varied to make use of the half-life differences. Additionally, if emitted beta radiations from two different nuclides

have substantially different energies, the low-energy betas can often be preferentially absorbed by a sheet of low-proton-number material such as Al (19).

In our preliminary work we did not require high photographic resolution. Better results can be attained (20) by reducing sample thickness, using thinner photographic emulsions, and reducing the distance between sample and emulsion.

Photographic film useful in this method is available in a wide range of sensitivities.-- Thermal neutron irradiation principally induces only two types of decay that affect emulsions: beta and gamma emission. Because it consists of charged particles, beta radiation is more effective. We investigated the effects of both types on high resolution plates, panatomic-x, no screen medical x-ray, and gravure copy films, all made by Eastman Kodak Co. Gravure copy film showed the least background fogging for mixed beta - gamma sources while still producing a usable image, so our subsequent work was done using this film. Beta radiation is about one hundred times more effective than gamma radiation on this emulsion (Fig. 1). Exposure threshold values for a minimum visible image were judged to be $3.8 \times 10^7$ radiations/cm$^2$ for betas and $8.5 \times 10^9$ radiations/cm$^2$ for gammas. Effects due to gamma radiation can normally be neglected, therefore, but gammas can be used in cases where betas are not produced or are screened out by an absorber.

Description of the Method

The method involves two steps: irradiation of a sample by thermal neutrons and exposure of the activated sample to photographic film.

The following relation is basic to the activation process:

$$A_s = f\sigma N \qquad (1)$$

where $A_s$ (saturation activity) is the highest level of activation, attained when production rate of a radioactive nuclide is in equilibrium with its decay rate, f is the thermal neutron flux of the irradiating source expressed in neutron/$cm^2$/sec, $\sigma$ is the cross section of the parent nuclide in barns ($cm^2 \times 10^{-24}$), ~~and N is~~ the number of parent nuclides in the sample, expressed in atoms/$cm^2$. N is derived from the relation

$$N = N_o \cdot \frac{W}{M} \cdot \frac{x}{100}$$

where $N_o$ is Avogadro's number ($6.02 \times 10^{23}$ atoms/mole), w is wt in gm of the parent element, M is the gram-molecular weight of the element, and x is the percent abundance of the parent nuclide.

Another important relation useful for nuclides with long half-lives is the activity level ($A_o$) of a daughter nuclide at the end of an irradiation that did not attain equilibrium. This will be some fraction of the saturation activity, as follows:

$$A_o = A_s \left[1-\exp\left(-\frac{.693t}{T_{1/2}}\right)\right] \qquad (2)$$

where t = duration of irradiation and $T_{1/2}$ is half-life of the daughter nuclide, both expressed in the same units.

In autoradiography by the method described here the photographic film is exposed by radiation from decaying daughter nuclides, so it is important to be able to estimate the number of disintegrations emitted by a sample in a given time interval after irradiation. The activity due to a single isotope decays exponentially according to the relation

$$A_t = A_o \exp\left(-\frac{.693t}{T_{1/2}}\right)$$

where t in this case is time elapsed since the end of irradiation. The number of disintegrations (D) between times "$t_1$" and "$t_2$" is

$$D = \int A_t dt = A_o \int \exp\left(-\frac{.693t}{T_{1/2}}\right) dt$$

therefore

$$D = -\frac{T_{1/2}}{.693} A_o \left[\exp\left(-\frac{.693t_2}{T_{1/2}}\right) - \exp\left(-\frac{.693t_1}{T_{1/2}}\right)\right] \qquad (3)$$

Note that the only quantities necessary to make this calculation for any given time interval are $A_o$ and $T_{1/2}$.

The total exposure given the film by all types of radiation can be calculated from the sum of D's for all decaying nuclides in the sample. In practice, the necessary exposure time can be estimated by studying the decay of a similar sample in a multichannel analyser.

Explanation of Table 1.

If the composition of a sample is known or can be estimated, Table 1 can be used to decide if the sample shows promise for autoradiography (21). Relative activities resulting from (n, $\gamma$) reactions in a thermal neutron flux have been calculated for all the listed nuclides, using equation (1) for saturation activity. While it takes an irradiation of about ten half-lives for a nuclide to reach saturation activity, it attains almost 94% of saturation activity in four half-lives, therefore we have set up a rule of convenience that saturation activity is essentially attained during four half-lives in the neutron flux. Since reactor irradiations are easily available up to 48 hours, we speak of a group of nuclides that attain equilibrium during a 48-hour irradiation or less (have half-lives of 12 hours or less) and a group of longer-lived nuclides (having half-lives greater than 12 hours) that do not attain equilibrium during a 48-hour irradiation. For these, instead of saturation activity, we have calculated initial activity at the end of a 48-hour irradiation, using equation (2). The listed isotopes are arranged in decreasing order of saturation activity or 48-hour activity, assuming irradiation times up to 48 hours. For the calculation it was assumed that a thermal neutron flux of $10^{11}$ n/cm$^2$/sec was used, and the sample consisted of one gm of the <u>element</u>. The activity values can be multiplied by a factor $10^{10}$ to obtain the results of the calculations; this is $10^{11}$ n/cm$^2$/sec x $10^{23}$ atoms/mole (part of

Avogadro's number) x $10^{-24}$ $cm^2$ (the cross-section coefficient). Other columns in Table 1 list half-life, and irradiation time necessary to produce the calculated activity.

Where a daughter nuclide decays only partially by electron or positron emission the calculated activity has been reduced according to the proportion of total disintegrations that produce electrons and positrons. An example of this is Eu, whose nuclide $Eu^{152m}$ has a calculated relative saturation activity of 26. Only 75% of its decay is by beta emission, however, while 25% is due to electron capture. Electron capture does not affect the photographic emulsion significantly in this case, so $A_s$ for $Eu^{152m}$ is given as 20.

Some elements have more than one stable nuclide that produces a radioactive daughter. In such cases, more than one isotope of the same element appears in the table. If sample irradiation times are adjusted to attain maximum activity for the longest half-lived isotope, the activity due to that element will be the sum of activities of all its listed isotopes. Such elements are listed in the table with the symbol (el.) replacing the mass number. An example is dysprosium (Dy), which has two useful daughter nuclides, one producing a saturation activity of 22.0 after a 9.3 hour irradiation, and the other producing a saturation activity of 5.3 after a 5 minute irradiation. The element can produce a relative activity of 27.3 after a 9.3 hour irradiation, but in some cases it might be better to settle for an activity of 5.3 and an irradiation time of 5 minutes.

Some elements produce daughter nuclides with very short half-lives. Those having less than a one-minute half-life are not considered useful for the present method, and are not listed in Table 1. Those with a half-life greater than one minute, however, can be useful; Fig. 2 shows an autoradiograph of a piece of aluminum foil that has been irradiated for two minutes in a measured thermal neutron flux of $2.89 \times 10^{10}$ n/cm$^2$/sec. The active daughter, $Al^{28}$, decays with a half-life of 2.4 minutes.

A correction that has not been made in the calculated values of Table 1 is that due to the geometry of the autoradiographic arrangement. Radiating sources in an activated sample are spherical, therefore in practice it is desirable to work with thin sections and locate photographic emulsions as close as possible to the sample to minimize image spread and enhance resolution. With such an arrangement the emulsion receives approximately half the radiation emitted by the sample; the other half is directed away from the film. The other geometrical corrections are usually quite small (22).

(Table 1)

Applications of the Method

The elements most commonly found in rocks are O, Si, Al, Fe, Mg, Ca, Na, K, and Ti. All the major rock-forming cations have one stable isotope that undergoes a reaction with thermal neutrons and produces beta radiation, but the usefulness of the method for any

element depends on its highest attainable activity in the sample and whether radiation from one daughter nuclide will mask radiation from another.

In Table 2, we have calculated activities for the major elements in one-gm samples of four rocks, assuming a 48-hour irradiation. The granite and diabase analyses (23) approximately represent end members of the major igneous rock units of the earth's crust; sandstone and limestone (24) are two very common sedimentary rock types. Those elements having high activities in the granite and diabase analyses are Al and Na, so these would be well suited to the method if their radiation effects do not interfere with each other. Reference to the half-lives in Table 1 shows that no interference need occur. Saturation can be reached for $Al^{28}$ during an irradiation of about 9 minutes, during which a negligible activity due to $Na^{24}$ will accumulate, therefore a film exposure can be made that will show the distribution of Al without interference from Na. A second irradiation can then be made for a 48-hour period, during which $Na^{24}$ will approach the saturation level. At the end of this second irradiation $Al^{28}$ will also be at the saturation level but its activity will become insignificant after decaying four to ten half-lives (8-25 min), and an exposure can then be made that will show the distribution of Na in the sample.

Of secondary importance is the effect due to K in the granite sample. Because they have similar half-lives radiation from $K^{42}$

and $Na^{24}$ will contribute to the same autoradiograph, and there is no way of avoiding it. Potassium, however, may be present in greater abundance in the orthoclase while Na tends to concentrate in the plagioclase, so the effects may not be confusing, and could be helpful.

Sodium and Al are present in very low concentrations in sandstone and limestone, so their calculated activity levels in these rocks are also low. Surprisingly, however, Al with a whole-rock concentration of only 2.5% in the sandstone, still has the highest activity in that rock. An autoradiograph of a sandstone that has this average composition, therefore, could give a picture of the distribution of Al - presumably in the cementing material.

The average limestone (Table 2) does not look too hopeful from the autoradiographic viewpoint, but see Fig. 3. This is an autoradiograph of a rock thin section in which the circular dark areas are cross-sections through fossil corals, and to the eye the matrix appears to be either calcite ($CaCO_3$) or dolomite [$(Ca,Mg,Fe)CO_3$]. Calcium, Mg, and Fe should activate only very weakly, as seen in Table 1, while C and O were not even included in the table, therefore neither the dolomite nor the calcite of the corals should stand out in the autoradiographic print. Obviously, autoradiography is only useful if it enables one to see something that he could not see more easily by another method. This autoradiograph is showing something quite interesting, namely

that other elements beside Ca, Mg, Fe, C, and O are present in the dolomite. This particular specimen had been irradiated for five hours, then allowed to decay for two and one-half hours before beginning the film exposure. During this time any initial $Mg^{27}$ would have disappeared, therefore the autoradiograph, which is a ten-hour exposure, actually produced a picture of the distribution of longer-lived nuclides in the sample. These were later identified by neutron-activation analysis as Mn, Na, and K, and the autoradiograph illustrates the fact that these elements are also present in appreciable concentrations in the matrix. It shows something else, as well - that they are not present in the corals.

A worker who wishes to make an autoradiograph must consider a number of factors before determining where to draw the line in Table 2 between suitable and unsuitable elements: the line will be drawn at different levels for different samples. Half-life will be a factor: obviously, of two elements having the same initial activity the one having the longer half-life can deliver more total radiation to the photographic emulsion, so equation (3) must be used after consulting Table 1. Also bulk concentration of an element will not always be a determining factor: many elements listed in Table 1 occur as accessory or trace elements in rocks. Their suitability for autoradiography will not depend on their bulk concentration but on their short-range distribution, since they will normally be found concentrated in the accessory minerals and their emissions will be concentrated on small areas of of the film.

In some cases it would be useful to outline concentration gradients of these accessory elements if they are associated with ore bodies. Examples might be found in low-grade uranium ores where the U occurs in association with V. V is one of the more favorable elements for activation, and in these cases its activated radiation could supplement the natural radiation emitted by U, with the net result that uranium ore could be detected in lower concentrations than would have been possible using only the natural emission. With this suggestion we have come full circle, back to the use to which autoradiography was first put.

In concluding, we leave our fields of specialization to suggest that perhaps the most important use of neutron-activation autoradiography could be in biological and medical studies. Where living organisms are involved, high radiation doses must be avoided unless, as in the case of a laboratory animal, it can be sacrificed after only a short while. There must be many situations where an experiment should be carried out over a long period of time, during which a particular element is assimilated only slowly into a physiological system. In most such cases radioactive tracers would kill the organism by prolonged radiation exposure, or impair its normal processes to the point where the experiment becomes invalid. In other cases tracer isotopes of the desired element might have too short a half life, and initial rations of the element would lose their detectability before the end of the experiment.

If a suitable nonradioactive element can be substituted for a tracer, long-term experiments can be carried out. When the

animal eventually dies or is sacrificed, sections of bone or teeth, or pieces of tissue may be activated to give autoradiographs showing the distribution of that element. For living subjects, biopsy samples could be treated in the same way.

Acknowledgement

We thank the NASA for support of this work through its research grant NsG-232 62. We thank Beverly Cassidy for calculating most of the data in Table 1. Irradiations were carried out at the Industrial Reactor Laboratories, Plainsboro, N.J. We thank Richard Pelrine and Daniel Ahrbach, of that laboratory, for their technical assistance.

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Table 1: Relative effects of thermal-neutron irradiation of certain elements, selected for their suitability in autoradiography.

| Daughter nuclide, or element | Mass No. | Initial Activity: $A_o$ ($10^{-10}$/betas/sec/gm) | Irrad. Time | Half-Life |
|---|---|---|---|---|
| Dy | (el.) | 27.3 | 9.3h | |
| Dy | 165 | 22.0 | 9.3h | 2.32h |
| Ir | 194 | 21.0 | 48.0h | 19.0h |
| Eu | 152m | 20.0 | 36.8h | 9.2h |
| In | 116m | 7.3 | 3.6h | 54.2m |
| Dy | 165m | 5.3 | 5.0m | 1.25m |
| Re | (el.) | 1.6 | 48.0h | |
| Mn | 56 | 1.5 | 10.3h | 2.58h |
| Lu | (el.) | 1.3 | 48.0h | |
| Lu | 176m | 1.2 | 14.8h | 3.71h |
| Au | 198 | 1.2 | 48.0h | 2.69d |
| Re | 188 | 1.2 | 48.0h | 17.0h |
| Ag | 108 | 0.86 | 9.2m | 2.3m |
| Sm | (el.) | 0.81 | 48.0h | |

| Daughter nuclide, or element | Mass No. | Initial Activity: $A_o$ ($10^{-10}$/betas/sec/gm) | Irrad. Time | Half-Life |
|---|---|---|---|---|
| Sm | 153 | 0.76 | 48.0h | 47h |
| Rh | 104m | 0.70 | 17.6m | 4.4m |
| V | 52 | 0.60 | 15.0m | 3.76m |
| Br | (el.) | 0.48 | 48.0h | |
| Pr | 142 | 0.41 | 48.0h | 19.3h |
| Re | 186 | 0.34 | 48.0h | 91.0h |
| Br | 80 | 0.32 | 74.0m | 18.5m |
| I | 128 | 0.30 | 100.0m | 24.98m |
| Rb | (el.) | 0.30 | 48.0h | |
| Rb | 86 | 0.30 | 48.0h | 18.6d |
| As | 76 | 0.25 | 48.0h | 26.6h |
| W | 187 | 0.24 | 48.0h | 24h |
| Cu | (el.) | 0.22 | 48.0h | |
| Yb | (el.) | 0.21 | 48.0h | |
| La | 140 | 0.20 | 48.0h | 40.2h |
| Yb | 175 | 0.19 | 48.0h | 4.2d |

| Daughter nuclide, or element | Mass No. | Initial Activity: $A_o$ ($10^{-10}$/betas/sec/gm) | Irrad. Time | Half-Life |
|---|---|---|---|---|
| Cu | 64 | 0.16 | 48.0h | 12.8h |
| Pd | 109 | 0.15 | 48.0h | 13.6h |
| Na | 24 | 0.12 | 48.0h | 15.0h |
| Br | 80m | 0.11 | 17.6h | 4.4h |
| A | 41 | .079 | 7.3h | 1.83h |
| Sb | (el.) | .076 | 48.0h | |
| Sb | 122 | .073 | 48.0h | 2.8d |
| Br | 82 | .069 | 48.0h | 35.9h |
| Ga | 72 | .068 | 48.0h | 14.2h |
| Lu | 177 | .067 | | 6.7d |
| Cu | 66 | .059 | 20.6m | 5.15m |
| Al | 28 | .051 | 9.2m | 2.3m |
| Er | (el.) | .051 | 48.0h | |
| Sm | 155 | .050 | 96.0m | 24.0m |
| Er | 171 | .048 | 30.0h | 7.5h |
| Tm | 170 | .045 | 48.0h | 127d |

| Daughter Nuclide, or element | Mass No. | Initial Activity: $A_o$ ($10^{-10}$/betas/sec/gm) | Irrad. Time | Half-Life |
|---|---|---|---|---|
| Ga | 70 | .039 | 84m | 21m |
| Gd | (el.) | .039 | 48.0h | |
| Y | 90 | .035 | 48.0h | 64.2h |
| Ge | (el.) | .034 | 5.47h | |
| Gd | 159 | .032 | 48.0h | 18.0h |
| Tb | 160 | .031 | 48.0h | 73.0d |
| Sc | 46 | .026 | 48.0h | 85d |
| Yb | 177 | .024 | 7.6h | 1.9h |
| Nd | (el.) | .022 | 48.0h | |
| Se | (el.) | .022 | 3.8h | |
| Os | (el.) | .020 | 48.0h | |
| Se | 81 | .019 | 72.8m | 18.2m |
| Ba | 139 | .019 | 5.67h | 85m |
| Zn | 69 | .017 | 3.47h | 52m |
| Ge | 75 | .017 | 5.47h | 82m |
| Ge | 75m | .017 | 5.51h | 82.7m |

| Daughter nuclide, or element | Mass No. | Initial Activity: $A_o$ ($10^{-10}$/betas/sec/gm) | Irrad. Time | Half-Life |
|---|---|---|---|---|
| Cl | 38 | .016 | 2.5h | 37.5m |
| Pt | (el.) | .016 | 48.0h | |
| Os | 193 | .014 | 48.0h | 31.5h |
| Te | (el.) | .013 | 37.4h | |
| K | 42 | .011 | 48.0h | 12.47h |
| Pt | 199 | .0087 | 124m | 31m |
| Ru | (el.) | .0084 | 48.0h | |
| Nd | 147 | .0082 | 48.0h | 11.3d |
| Cd | 115 | .0079 | 48.0h | 53h |
| Nd | 149 | .0077 | 8h | 2h |
| Ru | 105 | .0077 | 18.0h | 4.5h |
| Pt | 197 | .0073 | 48.0h | 18h |
| Te | 127 | .0071 | 37.4h | 9.35h |
| Gd | 161 | .0067 | 14.52m | 3.63m |
| Nd | 151 | .0066 | 48m | 12m |
| Os | 191 | .0055 | 48.0h | 16.0d |

| Daughter nuclide, or element | Mass No. | Initial Activity: $A_o$ ($10^{-10}$/betas/sec/gm) | Irrad. Time | Half-Life |
|---|---|---|---|---|
| Kr | (el.) | .0048 | 17.6h | |
| Co | 60m | .0048 | 42.0m | 10.5m |
| Hf | 181 | .0046 | 48.0h | 46d |
| Kr | 85m | .0041 | 17.6h | 4.4h |
| Mo | (el.) | .0038 | 48.0h | |
| P | 32 | .0036 | 48.0h | 14.3d |
| Sn | (el.) | .0036 | 48.0h | |
| Te | 131 | .0036 | 99.2m | 24.8m |
| Ce | 143 | .0030 | 48.0h | 33h |
| Er | 169 | .0027 | 48.0h | 9.4d |
| Se | 81m | .0027 | 3.8h | 56.8m |
| Mo | 99 | .0026 | 48.0h | 67h |
| Rb | 88 | .0024 | 71.2m | 17.8m |
| Pd | 111 | .0020 | 88m | 22m |
| Te | 129 | .0020 | 4.9h | 74m |
| Ni | 65 | .0019 | 10.0h | 2.5h |

| Daughter nuclide, or element | Mass No. | Initial Activity: $A_o$ ($10^{-10}$/betas/sec/gm) | Irrad. Time | Half-Life |
|---|---|---|---|---|
| Hg | (el.) | .0019 | 48.0h | |
| Sn | 121 | .0016 | 48.0h | 27.5h |
| Sb | 124 | .0012 | 48.0h | 60d |
| Mo | 101 | .0012 | 58.4m | 14.6m |
| Cr | 55 | .0010 | 14.0m | 3.5m |
| Hg | 203 | .0010 | 48.0h | 45.8d |
| Ti | 51 | .00092 | 23.2m | 5.79m |
| Ca | 49 | .00090 | 3.8h | 57m |
| Hg | 205 | .00088 | 22m | 5.5m |
| Zr | (el.) | .00080 | 48.0h | |
| Cs | 134m | .00077 | 12.8h | 3.2h |
| Mg | 27 | .00075 | 40.8 | 10.2m |
| Kr | 87 | .00075 | 5.2h | 78m |
| Si | 31 | .00074 | 10.6h | 2.65h |
| Ru | 103 | .00074 | 48.0h | 41d |
| Sb | $124m_1$ | .00063 | 5.2m | 1.3m |

| Daughter nuclide, or element | Mass No. | Initial Activity: $A_o$ ($10^{-10}$/betas/sec/gm) | Irrad. Time | Half-Life |
|---|---|---|---|---|
| Sb | $124m_2$ | .00063 | 84m | 21m |
| Xe | 137 | .00061 | 15.2m | 3.8m |
| Sn | 125m | .00061 | 38m | 9.5m |
| Zr | 97 | .00048 | 48.0h | 17.0h |
| Sn | 123 | .00038 | 2.67h | 40m |
| Bi | 210 | .00010 | 48.0h | 5d |
| S | 35 | .000032 | 48.0h | 87.1d |
| Fe | 59 | .000010 | 48.0h | 45.1d |
| Pb | 209 | .000009 | 13.3h | 3.32h |
| Sr | 89 | .000008 | 48.0h | 50.4d |

Table 2: Major-element compositions characteristic of certain rocks and calculated initial activities for one-gm samples.

| | granite (G-1) | | diabase (W-1) | | av. sandstone | | av. limestone | |
|---|---|---|---|---|---|---|---|---|
| element | wt% | $A_o(x10^{-6})$ | wt% | $A_o(x10^{-6})$ | wt% | $A_o(x10^{-6})$ | wt% | $A_o(x10^{-6})$ |
| Si | 33.9 | 2.5 | 24.6 | 1.8 | 36.6 | 2.7 | 2.4 | .18 |
| Al | 7.6 | 39. | 8.0 | 41. | 2.5 | 13. | 0.4 | 2.0 |
| Fe | 1.3 | .001 | 7.8 | .008 | 1.0 | .001 | 0.4 | .0004 |
| Mg | 0.2 | .015 | 4.0 | .30 | 0.7 | .052 | 4.8 | .36 |
| Ca | 1.0 | .09 | 7.8 | .70 | 2.5 | .22 | 30.4 | 2.7 |
| Na | 2.4 | 29. | 1.6 | 19. | 0.3 | 3.6 | 0.04 | .48 |
| K | 4.6 | 5.1 | 0.5 | .60 | 1.1 | 1.2 | 0.27 | .30 |
| Ti | 0.2 | .018 | 0.6 | .055 | 0.2 | .018 | 0.036 | .0033 |

## Figure Captions

Fig. 1. Curves showing measured densities in photographic images produced by gamma radiation (right) and beta radiation (left). We consider densities below the horizontal line unusable for printing without special treatment of the negative. Autoradiographs for the gamma-radiation curve were made with $Cr^{51}$, a pure gamma emitter. Those for the beta curve were made with $Si^{31}$, which produces only .07 percent gamma radiation and the rest betas.

Fig. 2. Autoradiograph of activated aluminum foil, showing that nuclides having short half-lives respond well to the method of activation autoradiography. Sample 2.6 cm long.

Fig. 3. Autoradiograph of a thin section of coral-bearing dolomite. The subcircular areas are sections through fossil corals and the light areas are the matrix dolomite. The dolomite has been activated significantly, while the corals show very low activity probably due only to calcium. Sample USGS 20546, 2 cm long.

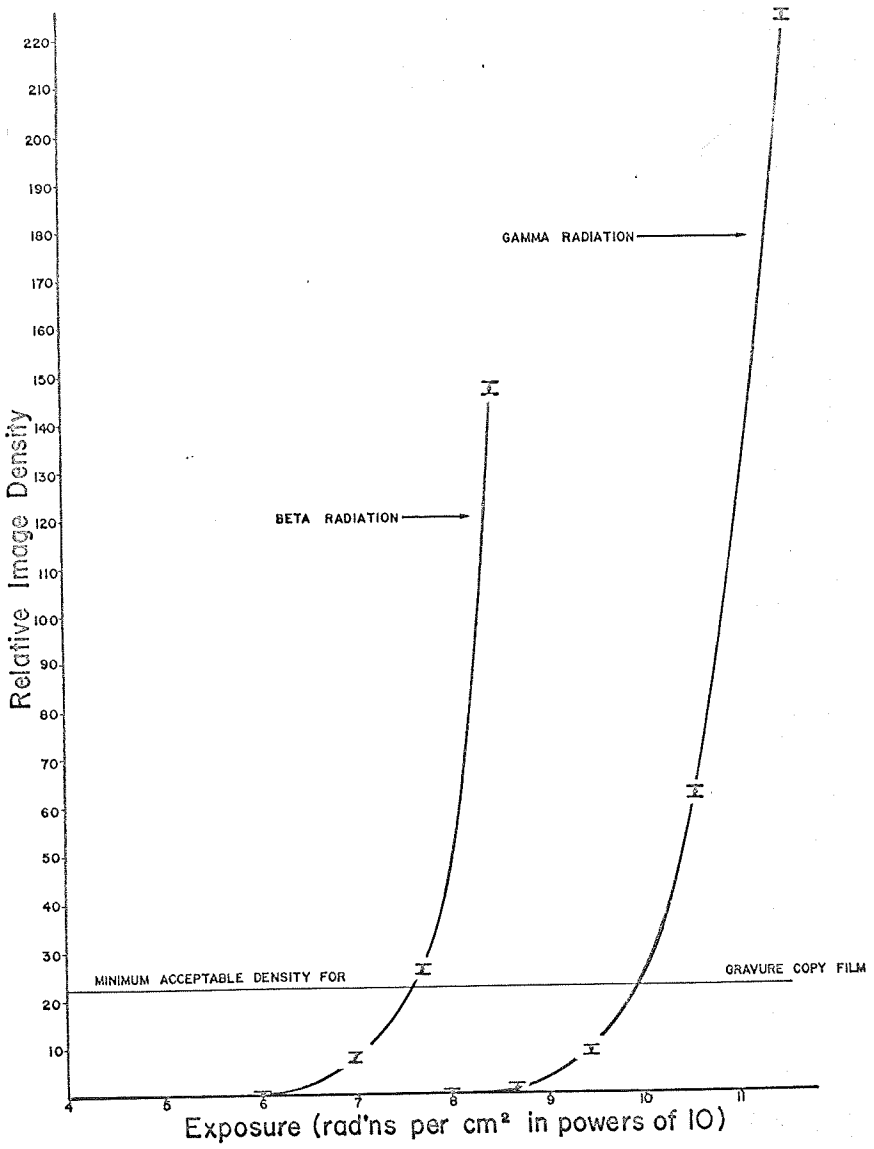
Relative Image Density
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
GAMMA RADIATION
BETA RADIATION
MINIMUM ACCEPTABLE DENSITY FOR
GRAVURE COPY FILM
4
5
6
7
8
9
10
11
Exposure (rad'ns per cm² in powers of 10)

Figure One

Figure Two

Figure Three