Reports

X-ray Visualization and Analysis of Multicomponent Subjects

Abstract. The information carried by x-rays showing the distribution of each material of which a subject is assumed to be composed is distributed on separate films by means of a controlled variation in composition of the scanning radiation. The beam is modulated, for example, by simultaneous motion of several wedges. The method is useful in quantitative x-ray analysis and as a system for making radiographs predominantly sensitive to one material in the subject.

The usual radiographic methods discard information by lumping the effects of the subject on a number of x-ray wavelengths into a single monochrome display (black and white radiograph). Some additional information about subject absorption and its rate of change with wavelength can be presented to the eye in the form of a colored image or print that is formed from "separation negatives" made by taking two or three radiographs with differing incident x-ray wavelength distributions (*1*). A possibility exists for the study of a many-component system in which each component is separately mapped for distribution density, the survey of all components taking place simultaneously.

This method can most conveniently be understood as a generalization of a simple scheme. Suppose a monochromatic x-ray beam traverses a wedge of some material and then falls upon an intensity detector whose output controls the wedge position in such a way as to bring the detected intensity to a preset value. Then if a sample of this same material is also inserted in the beam, the wedge will move out in such a way as to leave the total amount of this material in the beam fixed. The distance the wedge moves out is proportional to the amount of the material introduced. The motion can be recorded on a film as a variable darkening, and scanning the subject thus provides a radiograph showing the over-all distribution of this material. The same thing is true if there are j wavelengths, each maintained at constant intensity, and j materials. Each wedge will then move independently of the rest to indicate the amount of its material in the subject. The motion of all the other wedges cancels fluctuation in amount of substances other than the one of interest. There result j monochrome images for later individual study, each depicting the distribution of one material. This can be considered either as a method of quantitative analysis, or as a method of radiography.

It is possible to prove that under equilibrium conditions there is a unique endpoint. In the proof one also finds the condition that substances be considered distinct and thus distinguishable. In Fig. 1 is shown a schematic representation of the system. Each of the j wavelengths m is assumed to be attenuated to a fixed intensity fraction k by traversing the subject and wedges. If μ_{nm} is the absorption coefficient of the nth material for the mth wavelength, then there is one equation for each λ that expresses the outgoing intensity in terms of the traversed thickness of each of the materials:

$$\sum_{n=1}^{j} - \mu_{nm}\, t_n = \log k_m$$

Thus there are j simultaneous algebraic equations in the thicknesses of the j materials (wedge plus wedge-material in the subject). The quotient of two determinants gives the value of t traversed in any one material. One of the determinants is made up of the μ's and the other is made up of the μ's and k's, and thus each t is a number (a constant). This shows that, at equilibrium, the total amount of each material in the beam is individually constant. Thus, for example, if 1 g/cm² of a material is present in the unknown, then *that* wedge will move out by an amount exactly equivalent to 1 g/cm².

The previous is true if the coefficients of t are such that no two equations are "derived equations." This gives the precise definition with which the term "distinct materials" is here used. The observed laws of x-ray absorption are such that different elements tend to be distinct. Essentially two materials are distinct if their absorption curves, as a function of wavelength, do not have pairs of proportional ordinates in the range of wavelengths used.

The greater the differences in the way absorption varies between the materials, the greater are the unbalance signals. Thus, for maximum sensitivity, it is advantageous to work around absorption discontinuities or edges.

The control signal to any one wedge will vanish at equilibrium if it is any linear combination of the error signals from the detectors. Circuitry that worked in a two-wedge experiment will be cited, but the best general system for good transient response has not yet been fully investigated. Though it does not assure that a corrective signal will be applied only to the wedge that is out of position, it does seem desirable that the signal to any one wedge be made of a sum of the phototube signals, each weighted by the μ of that wedge for the λ in question. This directs corrective effort at a given λ predominantly to the material which most affects this λ, rather than encouraging large excursions by the other wedges.

The j wavelengths can either follow

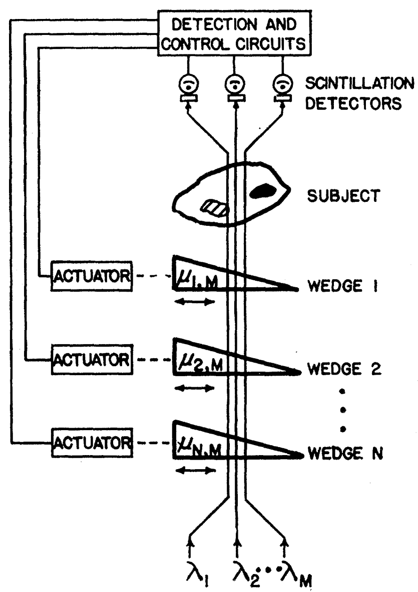

Fig. 1. If the wedges move so that the intensity of each emerging x-ray is constant, then each wedge position indicates the amount of its material at the traversed place in the subject. For example, if there are three wedges and three wavelengths, then by scanning the subject, one obtains three maps or radiographs, each depicting the distribution of one of the three materials in the subject.

Instructions for preparing reports. Begin the report with an abstract of from 45 to 55 words. The abstract should *not* repeat phrases employed in the title. It should work with the title to give the reader a summary of the results presented in the report proper. (Since this requirement has only recently gone into effect, not all reports that are now being published as yet observe it.)

Type manuscripts double-spaced and submit one ribbon copy and one carbon copy.

Limit the report proper to the equivalent of 1200 words. This space includes that occupied by illustrative material as well as by the references and notes.

Limit illustrative material to *one* 2-column figure (that is, a figure whose width equals two columns of text) or to *one* 2-column table or to *two* 1-column illustrations, which may consist of two figures or two tables or one of each.

For further details see "Suggestions to Contributors" [*Science* 125, 16 (1957)].

each other in succession onto one detector or they can all act simultaneously onto j detectors. The beams must all traverse the same region of the subject and so, because of this and drift considerations, a single detector is felt to be best even though some sort of memory or gating circuit is then required.

A piece of equipment already under construction in Sweden for a related operation was modified as a joint effort to test this new principle. The experimental arrangement and some results have been given (*1*). In this case the scheme was adapted to the detection of iodine (either the quantitative analysis of that normally present in human beings, or the sensitive mapping of a standard x-ray contrast medium). The two wedges were made of iodine and of plastic, the latter being similar to soft tissue. The monochromatic wavelengths were supplied alternately by a pair of rotating secondary emitters (fluorescent radiation). These wavelengths were chosen to fall just on opposite sides of the iodine k absorption edge for maximum sensitivity.

The position of the plastic wedge was automatically adjusted through suitable gating circuits to bring the longer wavelength always to a preset intensity value. The a-c component in the detector signal, as the two wavelengths alternated, was brought to zero by control of the iodine wedge position. This then brought the intensity of the shorter wavelength also to the preset value. The two wedges steadily hunted, at slightly different frequencies, in a small range about their proper positions, as hoped. Wedge position was used to control the frequency of a flashing light which blackened a film during the scanning process. Thus the iodine distribution was mapped.

Jacobson independently reported some observations with the unit (*2*) and noted that fat does not seem to act like water. Thus three wedges would be more suitable. He noted that 1 g of fat per square centimeter acted like 0.5 mg of iodine per square centimeter.

Nonuniform irradiation of the subject —for example, by applying most of the dose around the edges of the structure— can reduce the total dose to a subject in producing a given image quality; but constant-output intensity systems such as the present one tend to minimize dose (*3*). Another property of such systems is that they can be compensated against source-intensity fluctuations with an auxiliary detector and difference amplifier, rather than with a ratio detector.

From dose considerations this procedure is most practical in human beings for the relatively heavy elements because the lighter ones demand "soft" highly absorbed wavelengths, if use is to be made of absorption edges. Possibly heavier elements should be used in contrast media for this reason (at least for use in retrograde application). A similar system may have application in the ultraviolet, and the optical analog is sometimes a convenient guide to thought (*4*).

R. STUART MACKAY
Radiological Research Laboratory, University of California Medical Center, San Francisco

References and Notes

1. For discussion of this see B. Jacobson and R. S. Mackay, *Advances in Biological and Medical Physics*, J. H. Lawrence and C. A. Tobias, Eds., (Academic Press, New York, 1958), vol. 6, pp. 201–261.
2. B. Jacobson, paper presented at the International Conference on Medical Electronics, Paris, 28 June 1958.
3. R. S. Mackay, *Brit. J. Radiol.* 31, 642 (1958).
4. This method was conceived while I was on leave from the University of California as a Guggenheim fellow.

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Geochemical Scavenging of Strontium

Abstract. Crandallite, an abundant mineral belonging to the alunite structure type, is a geochemical host for ordinary strontium in the soil profile and the deeper ground-water circulation. It may be useful in the scavenging or storage of the radioisotopes of strontium and certain other elements.

The chemical action by ground waters of the deeper meteoric circulation and of the zone of weathering on pre-existing rocks results in the formation of secondary minerals appropriate to the new environmental conditions. Certain of the minerals of the original rock that are resistant to chemical attack also may accumulate as residual deposits, and other material may be yielded in soluble form and ultimately removed in the surface drainage.

Elements present in trace amounts in the original rock, if not removed in solution, may be concentrated and redeposited locally by the ground waters either as specific compounds or in solid solution in variable amounts in certain other more abundant minerals. Adsorption and cation-exchange mechanisms also may be operative. The natural geochemical and crystallochemical behavior in the ground-water circulation of strontium and of other trace elements of interest in connection with radioactive wastes and fallout may be informative in relation to the artificial storage or scavenging of the radioisotopes of these elements in ways that involve geological environments and materials.

With regard to strontium, the hitherto known host minerals for this element are operative chiefly in the magmatic and sedimentary cycles. A few, such as members of the aragonite and barite structure types, are of consequence in the deeper ground-water circulation. None of these minerals normally form in, or are stable in, the soil profile, where they could act as hosts, and it has been generally believed that strontium released during weathering is retained in soluble form in the soil waters.

Recently, it has been established (*1*) that minerals of the alunite structure type also are specific geochemical hosts for strontium. Crandallite, $CaAl_3(PO_4)_2(OH)_5H_2O$, is of particular interest. In crandallite deposits of the deeper circulation, such as those of the Fairfield, Utah, type, where descending phosphatic solutions derived from marine phosphate-rock formations have reacted with argillaceous limestone, the crandallite is enriched in strontium. Crandallite develops analogously in the soil profile during the weathering of phosphatic limestone and marine phosphorites. The occurrence of crandallite in this way has been recognized only in recent years (*2*), and little is known of the extent of such occurrences over the world. The surficial crandallite deposits of one area in the Florida Gulf coastal region have been estimated at upwards of 800 million tons. The Senegal deposits are larger and have been mined for their phosphate content, but the resources are not known. Although the available data are very scant, the Senegal crandallite contains up to at least 0.50 percent SrO by weight, and it appears to be enriched in Sr over the phosphate rock from which it was derived.

The formation of crandallite by natural processes in the zone of weathering is restricted to areas of favorable bedrock and ground-water composition, and the mineral is not a constituent of soils in general. However, since it is stable under neutral and alkaline conditions, it probably would remain unchanged, without further control of the soil pH, if added to most soils. The availability of the mineral and its known ability to house strontium by both crystallization and cation-exchange mechanisms suggests that it possibly may be of interest as a scavenger in arable soils and as a vehicle for the storage of radioactive wastes. Knowledge of areas in which crandallite is a natural constituent of the soil profile would be pertinent to any general study of the distribution of strontium between the hydrosphere, the lithosphere, and vegetation.

In the alunite structure type (*3*), the monovalent and divalent ions are held in relatively open 12-coordinated positions that are very tolerant with regard to both the size and the valence of the contained