NEUTRON ACTIVATION ANALYSIS

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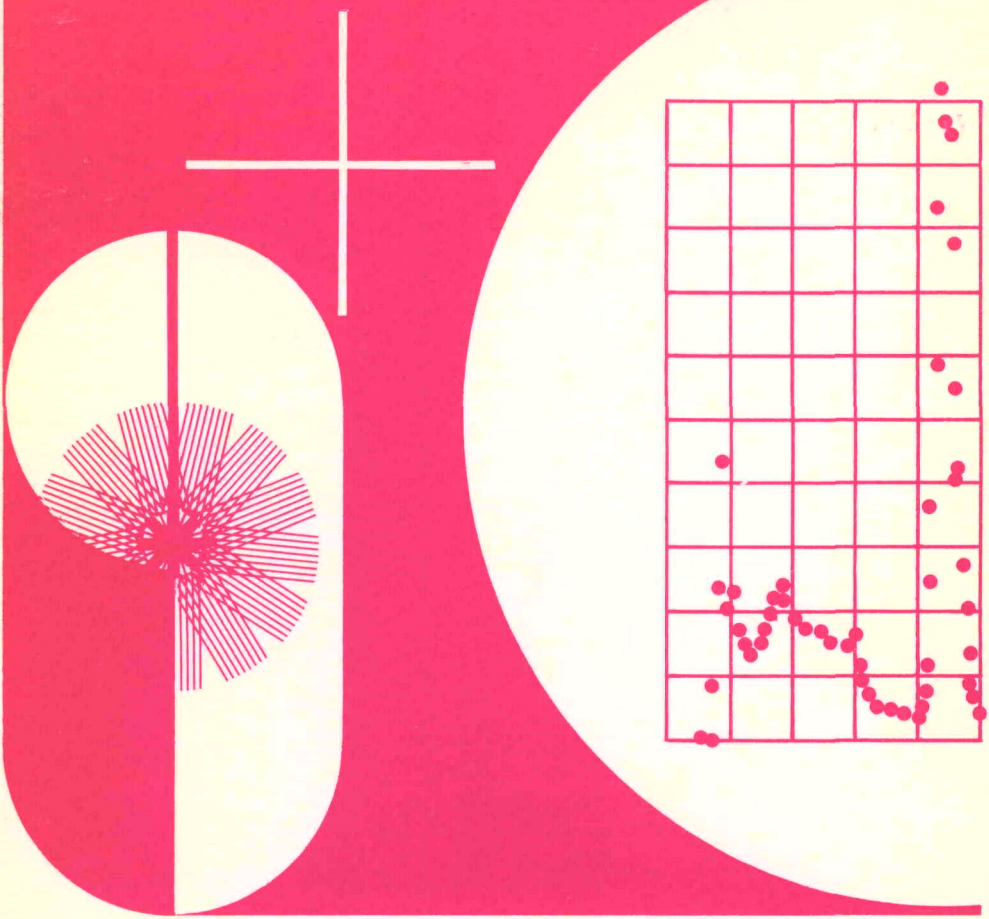

U.S. ATOMIC ENERGY COMMISSION / Division of Technical Information

ONE
OF A SERIES ON
UNDERSTANDING THE ATOM

UNITED STATES
ATOMIC ENERGY COMMISSION

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Nuclear energy
is playing a vital role
in the life of
every man, woman, and child
in the United States today.
In the years ahead
it will affect increasingly
all the peoples of the earth.
It is essential
that all Americans
gain an understanding
of this vital force if
they are to discharge thoughtfully
their responsibilities as citizens
and if they are to realize fully
the myriad benefits
that nuclear energy
offers them.

The United States
Atomic Energy Commission
provides this booklet
to help you achieve
such understanding.

Edward J. Brunenkant
Director
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Library of Congress Catalog Card Number: 63-64916

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He is the author of *Propulsion Systems for Space Flight* (McGraw-Hill 1960); *Direct Conversion of Energy* and *Power Reactors in Small Packages*, preceding booklets in this series; as well as numerous articles and papers for technical journals and conferences.

NEUTRON ACTIVATION ANALYSIS

By William R. Corliss

A criminal goes to jail because he carried a minute speck of evidence away from the scene of a crime. A meteorite is analyzed to billionths of a gram to reveal traces of elements it brings from space. Testing of contraband opium reveals its geographical source.

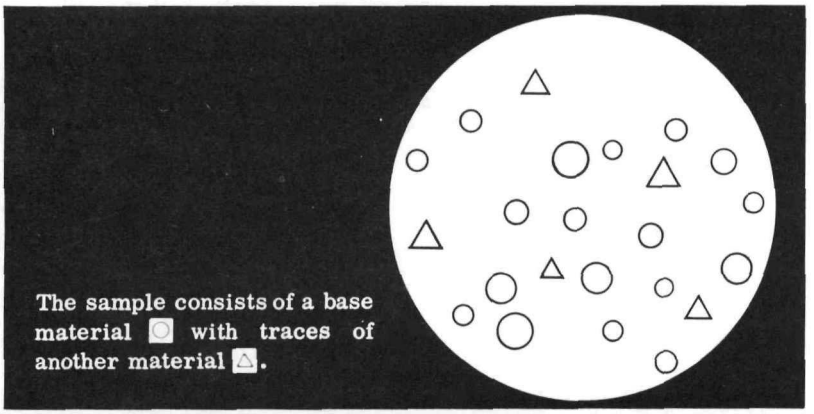
What do these dissimilar events have in common? All involve identification of materials by activation analysis, *a sensitive, versatile analytical tool employing nuclear energy.*

SOME FUNDAMENTALS

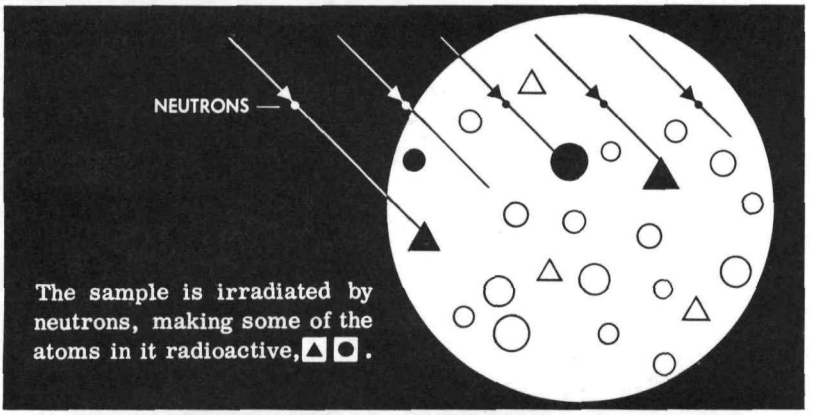
In activation analysis a sample of an unknown material is first irradiated (*activated*) with nuclear particles. In practice these nuclear particles are almost always neutrons, hence the title of this booklet. The irradiated atoms are

HOW ACTIVATION ANALYSIS WORKS

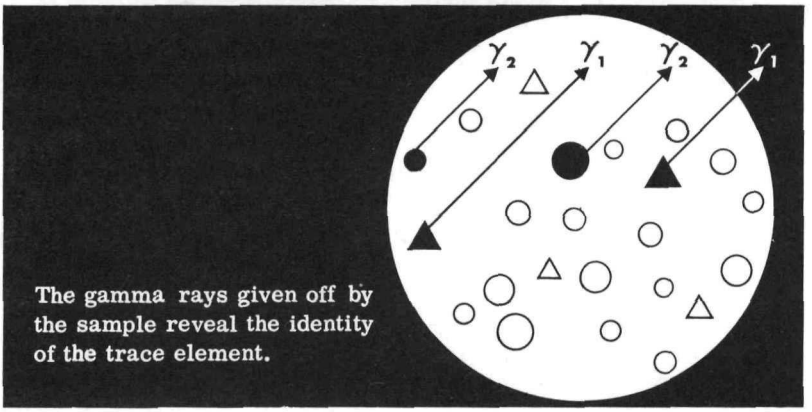
In activation analysis, traces of various elements can be identified and measured by analyzing the gamma rays they give off after being irradiated with neutrons or other nuclear particles.



The sample consists of a base material ○ with traces of another material △.



The sample is irradiated by neutrons, making some of the atoms in it radioactive, ▲ ●.



The gamma rays given off by the sample reveal the identity of the trace element.

made radioactive by the neutrons. They disintegrate with the emission of high-energy electromagnetic radiations called gamma rays. The gamma rays are next counted (*analyzed*), a process which reveals the half-lives* of the radioactive nuclei and also their gamma-ray energies. These nuclear "fingerprints" can then be located in specially prepared tables of data to identify the artificially created nuclei and by inference the elements in the original nonradioactive material as well.

The success of activation analysis depends upon nuclear reactions which are completely independent of an atom's chemical associations. Thus, the nuclear fingerprint identifies chemical elements, but not chemical compounds.

BEGINNINGS AND RAPID GROWTH

The value of activation analysis as a research tool was recognized almost immediately upon the discovery of artificial radioactivity by the famous husband-and-wife team, Frederic and Irene Curie-Joliot, in 1933. The first activation analysis experiment was carried out in 1936 by the Nobel prize-winning Hungarian, George Hevesy (one of the first users of radioactive tracers), and Hilde Levi in Copenhagen when they bombarded impure yttrium with neutrons to activate and measure the contaminant, a small quantity of dysprosium. From this point, activation analysis caught on rather slowly, awaiting developments in the two basic components in any activation analysis facility, namely, the radiation source and the gamma-counting equipment.

After World War II nuclear reactors with their copious neutrons became available. In addition, substantial strides have been made recently in the manufacture of other effective neutron sources, costing far less than reactors. Coupled to these advances has been the wizardry of modern electronics which has given us gamma detection and measuring equipment with a sensitivity unheard of at the time of the Curie-Joliots.

---

*Half of the radioactive atoms in a sample will disintegrate in one half-life.

Such technological vigor has widened the horizons of activation analysis to the point where it is now usefully engaged in such diverse areas as:

Petroleum	Analyzing oil refinery feeds for vanadium
Agriculture	Detecting pesticide residues on crops
Electronics	Measuring impurities in silicon semiconductors
Astronautics	Possible determination of the compositions of the lunar and planetary surfaces
Metallurgy	Measuring trace impurities
Criminology	Identifying gunpowder residues
Geology	Analyzing minerals
Medicine	Tracing metals in metabolism

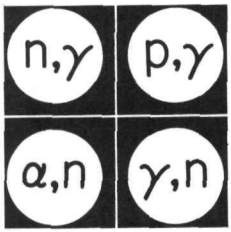
AN ACTIVATION ANALYSIS EXPERIMENT

Let us now examine the processes involved in activation analysis in a little more detail. We can do this by considering them from the point of view of a student taking a final examination.

In the classical final examinations in college analytical chemistry, the student is given an unknown substance to identify. He proceeds with the gravimetric tests, the colorimetric tests, the taste test (if he is old-fashioned), and the whole gamut of standard chemical determinations. When he is finished, hours or days later, he gets a passing mark if he has properly identified the major elements and compounds and determined their relative percentages by weight.

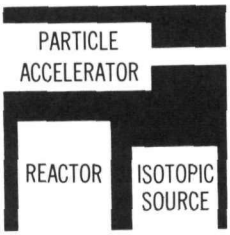
The (hypothetical) activation analysis student receives a similar sample, but goes through an entirely different set of considerations.

His approach is something like this:



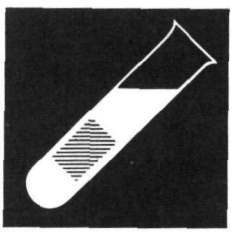
1. SELECT THE BEST NUCLEAR REACTIONS

A wise choice of reactions will amplify the presence of the elements of interest and suppress the activations of other elements. The trace elements that are to be identified and measured have different cross sections for slow (or thermal) neutrons, fast neutrons, protons, and gamma rays. For example, hydrogen and carbon, both common in organic substances, are scarcely activated by thermal neutrons.*



2. CHOOSE A RADIATION FACILITY

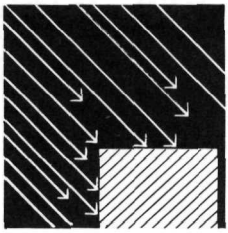
After picking the best nuclear reactions, the analyst must find an appropriate source of bombarding neutrons. Three important kinds of neutron sources are available: (1) nuclear reactors with relatively high neutron fluxes; (2) charged-particle accelerators that can manufacture intermediate fluxes of neutrons; and (3) low-flux radioactive neutron sources. (See photographs on pages 20 and 21.) High fluxes increase the sensitivity of the analysis. Not unexpectedly, however, high fluxes also cost more.



3. PREPARE THE SAMPLE

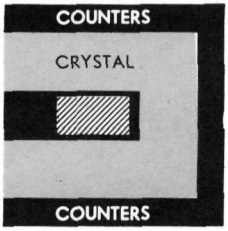
The selected neutron source may impose size restrictions on the sample, or perhaps the sample will have to be specially cooled in a reactor. Chemical processing of the sample is occasionally necessary to remove elements that emit interfering radiation. Special care must be exerted in handling the sample. For example, the touch of a finger can sometimes transfer enough salt to a sample so that the gamma rays from the salt's sodium will interfere with the sensitivity of the experiment.

**The nuclear cross section is proportional to the probability that the bombarding particles will activate the target nuclei.*



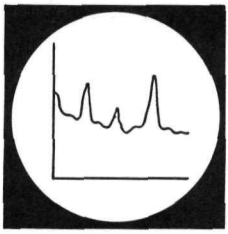
4. IRRADIATE THE SAMPLE

The neutron source is then turned on, shooting neutrons into the sample. This radiation makes some of the nuclei radioactive. The irradiation exposure time depends upon the sensitivity desired, the nuclear cross sections involved, and the half-lives of the radioisotopes produced. Thus, if the atoms being scrutinized decay rapidly, it is useless to irradiate the sample for a long period of time.



5. COUNT THE IRRADIATED SAMPLE

The irradiated sample is placed within a gamma-ray counter which records the numbers and energies of the gamma rays given off. The gammas are automatically sorted out by their energies, and those in each energy group are added up. These jobs are done by means of an electronic device called a multichannel differential analyzer. The results are then presented to the experimenter either on an oscilloscope, or they are printed, or punched out on computer cards.



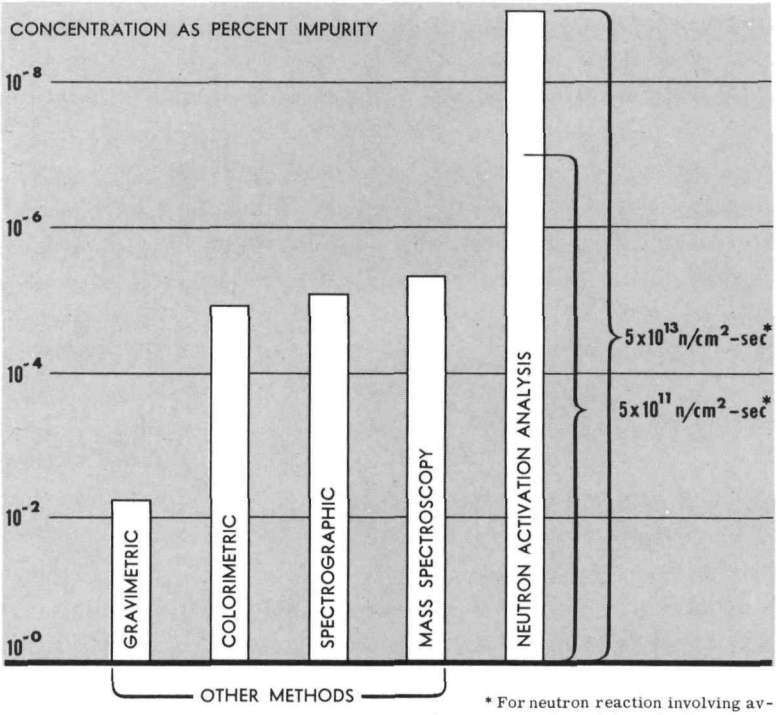
6. INTERPRET THE DATA

The experimenter compares the radiation of the known control sample with that of the unknown substance being tested. Relative concentrations may be found directly. Or, if the fluxes and cross sections are known well enough, the concentrations can be calculated without the aid of a control. At the conclusion of the experiment, the constituents can be identified and measured within a per cent or two accuracy. Under favorable conditions and high neutron fluxes, quantities as low as one billionth of a gram of some elements can be measured and detected. If mere comparison of materials is desired for purposes of identification, as in criminology, the nuclear fingerprints can be compared directly.

PROS AND CONS

Just how does activation analysis compare in effectiveness with other types of analysis, such as spectroscopic, gravimetric, and colorimetric analysis? The bar graph shows that activation analysis is potentially more sensitive, by an order of magnitude, for elements with high nuclear cross sections.* It shows further that greater sensitivities can be attained when high-flux reactors are used for irradiating

NEUTRON ACTIVATION ANALYSIS SENSITIVITY



* For neutron reaction involving average elemental activation cross section of 0.5 barn.

Comparison of the sensitivity of neutron activation analysis with other types of analysis. The sensitivity of activation analysis varies with the flux level, the time used for irradiation, the type of particle used, and the element itself.

*Nuclear cross section is measured in a unit called a barn, which is equal to 10^{-24} square centimeter.

the sample. Some other advantages of activation analysis are its speed and the fact that is usually does its work without damaging the sample or specimen.

Its major disadvantage is the fact that it costs more at present. Activation analysis costs may be a factor of two or more higher than those of more conventional techniques if high-flux reactors have to be used. In addition, activation analysis cannot discern combinations of atoms (chemical compounds), which various methods of chemical analysis are able to do.

SOME APPLICATIONS

ARSENIC IN NAPOLEON'S HAIR

The uncanny ability of activation analysis to detect and identify very tiny amounts of certain elements has come to the aid of law-enforcement officers in a variety of ways.

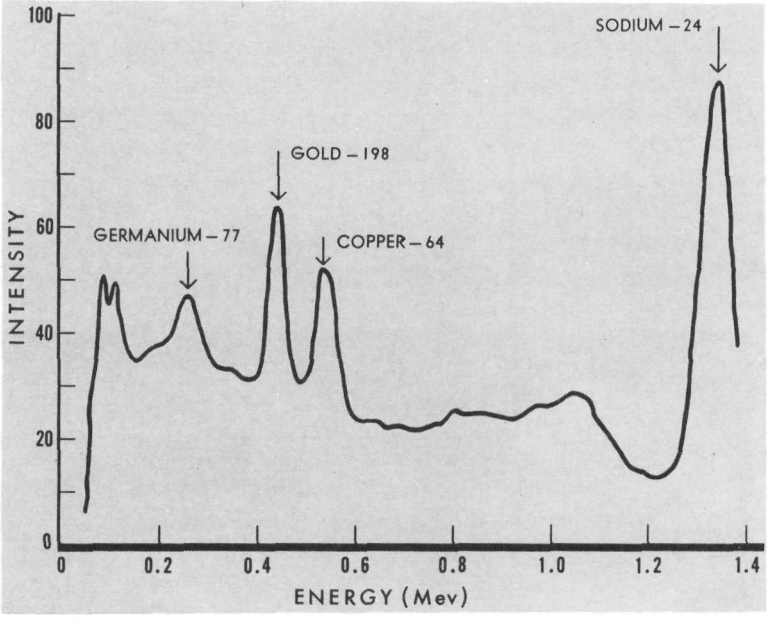
Human hair, for example, contains small traces of metallic elements like sodium, gold, and copper. Activation analysis has shown that the quantities of these elements present in each hair are relatively constant for an individual but vary from person to person. A recent murder conviction in Canada was based partly on the fact that a hair found in the hand of the murder victim matched the suspect's hair when the nuclear fingerprints were compared. The French courts also have admitted activation analysis data as evidence in criminal cases.

The fact that a person died from poisoning can sometimes be determined through activation analysis. Even nonlethal doses of arsenic, for example, produce arsenic-rich regions in the subject's hair that gradually move from root to tip as the hair grows. Hair even hundreds of years old can be analyzed successfully for arsenic and other residues.

English scientists recently found an unusual amount of arsenic in a relic of hair from Napoleon's head. The suspicion now is that he was slowly poisoned to death.

The case of King Eric XIV of Sweden is similar. A murder legend has persisted in Sweden for four centuries. When the king's body was exhumed recently, activation anal-

GAMMA-RAY SPECTRUM OF HAIR



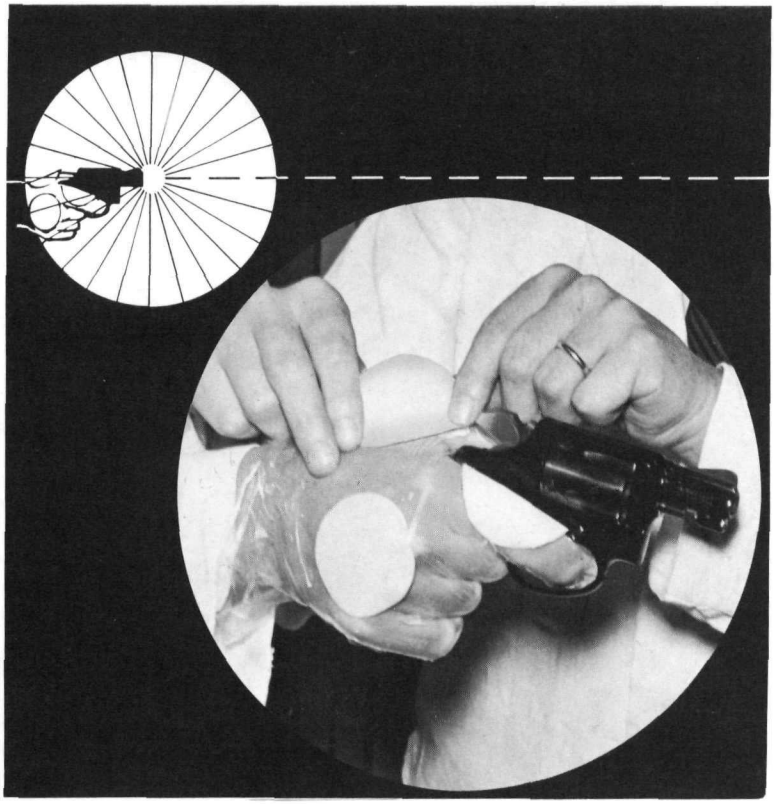
Gamma-ray spectrum of a neutron activated human hair. The peaks are created by activated metals normally present in hair in minute amounts. Since everyone has a slightly different hair spectrum, activation analysis is a useful identification tool.

ysis showed that his body contained traces of poisonous arsenic.

Activation analysis goes beyond these ghoulish activities in helping to solve crimes. Besides being able to match human hair, it can also compare infinitesimal grease spots, specks of dirt too small to be seen with the naked eye, and tiny flakes of paint from automobiles in accidents. It can do this in either of two ways. It can either match bits of material left behind at the scene of a crime to a suspect, or it can identify minute traces of substances that he has carried away from the scene. What's more, identification can be made without damaging the specimens. Thus, they can later be admitted as evidence in court.

Investigation by Dr. Vincent Guinn at General Atomic Division, General Dynamics, San Diego, California, shows that activation analysis of wipings taken from a suspect's hands will reveal not only whether he has fired a gun recently but also the type of ammunition used, the number of bullets fired, and the hand in which the gun was held. This is possible because when a gun is discharged gunpowder residues spread over a wide area, including the holder of the gun. These residues contain small amounts of various metals that can be measured easily by activation analysis.

GUNPOWDER FLASHBACK EXPERIMENT



Activation analysis experiment to measure the distribution of gunpowder residues left on a "suspect's" hand after the firing of a revolver. Courtesy General Atomic.

The incredible sensitivity of activation analysis in detecting gunpowder traces is evident in the following data taken after a test during which a subject fired a gun twice, using different types of ammunition:

SAMPLE	ELEMENTS FOUND IN HAND WIPING (MICROGRAMS)			TYPE OF AMMUNITION
	Antimony	Barium	Copper	
Left hand	0.03	0.20	1.73	Peters
Right hand	0.09	0.30	3.80	
Left hand	0.11	0.29	1.94	Western
Right hand	0.20	0.35	7.20	

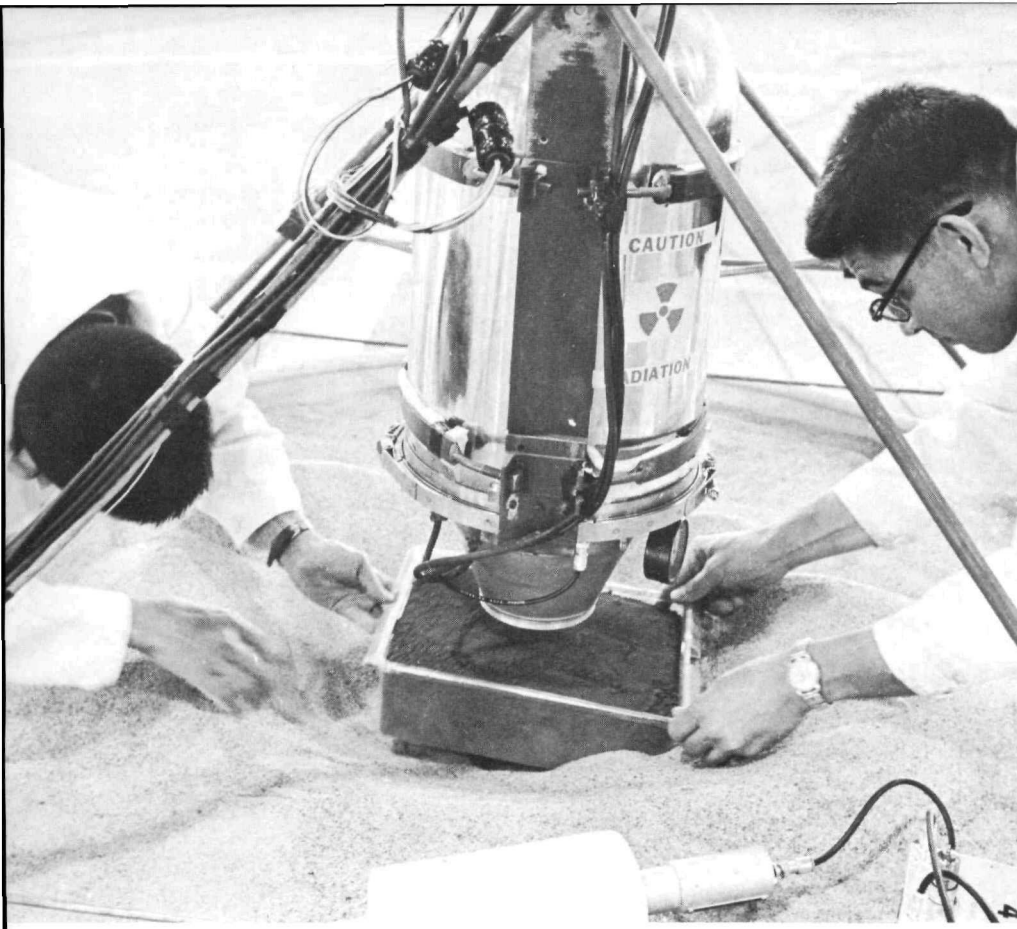
It can be seen that, while the relative amounts of metals in the gunpowder varied from one brand of ammunition to the other, the subject quite obviously used his right hand in each firing.

SAMPLING THE MOON'S SURFACE

Prospective human explorers of the moon have a problem. They don't know what its surface is really like. Will they "drown" in a deep layer of fine dust or find vast seas of rock rubble? Identification of the minerals on the surface of the moon will help the geologist unravel some of the mysteries.

The experiment might be done remotely from the earth in the following way: A small, unmanned spacecraft settles slowly to the lunar surface as its descent is braked by landing rockets. Once on the surface, a source of fast neutrons is switched on by a radio signal from earth. The neutrons penetrate into the lunar crust or dust, as the case may be, and activate some of the elements. The neutron source is turned off, and the gamma-ray counter in the same instrument package analyzes the radiation from the lunar material. The data are telemetered back to earth.

The information received back at the earth gives the identities and relative concentrations of elements in the



Activation analysis equipment designed for use on the lunar surface. Here, it is shown being checked out against samples of material which might occur on the moon. The equipment shoots a beam of 14-Mev neutrons into the sand and rocks and measures the gamma rays that are emitted by the radioactive atoms that are created. Courtesy Texas A. & M. College.

lunar crust. From such knowledge, inferences can be drawn about the identity of minerals and other chemical compounds.

The lunar surface experiment differs from most activation analyses in that the major components in a mixture of elements must be measured rather than traces of minor constituents. In addition, several of the lighter elements that comprise many terrestrial (and presumably lunar) minerals are very difficult to activate with slow neutrons.

Consequently attention has been turned to the possible use of fast neutrons. Some reactions under consideration are:

TARGET ELEMENT	ACTIVATED NUCLEUS	REACTION*	GAMMA-RAY ENERGIES (MEV)†	HALF-LIFE‡
Aluminum-27	Magnesium-27	$Al^{27}(n,p)Mg^{27}$	0.83, 1.01, 0.18	9.45 min
Iron-56	Manganese-56	$Fe^{56}(n,p)Mn^{56}$	0.84, 1.81, 2.13	2.58 hr
Magnesium-24	Sodium-24	$Mg^{24}(n,p)Na^{24}$	2.75, 1.37	15 hr
Silicon-28	Aluminum-28	$Si^{28}(n,p)Al^{28}$	1.78	2.27 min

*Nuclear-reaction shorthand: Target element (neutron in, proton out) activated element.

†1 Mev = 1,000,000 electron volts. The electron volt is a unit of energy equal to 1.6×10^{-19} watt-sec.

‡Half-life of activated atom.

The production of fast neutrons in a miniaturized instrument suitable for use on a lunar vehicle has already been achieved by researchers at the AEC's Lawrence Radiation Laboratory at the University of California. A small electrostatic accelerator bombards a tritium* target with deuterons,* producing 14-Mev neutrons in the resulting fusion reaction. The accelerator, counter, and associated electronic equipment are compressed into a small package suitable for launching into space.

Thus, if all goes well, the first lunar geologist may well be a neutron source and gamma-ray counter.

TRACING TRACES IN BIOLOGY AND MEDICINE

While living material is composed mainly of carbon, hydrogen, oxygen, and nitrogen, the presence or absence of other elements can have a profound effect on the well being of an organism. Napoleon and the arsenic make a good case in point. Since activation analysis is at its best when searching for and measuring minor constituents, it is proving valuable in a variety of biomedical, trace-element applications. Thus, it is being used in several laboratories to measure the concentrations of magnesium, copper, zinc,

*Tritium is a hydrogen isotope with two neutrons and a proton in its nucleus. Deuterium is also hydrogen, but with one less neutron in the nucleus. A deuteron is an ionized deuterium atom.

and other metals in human blood. Magnesium, for example, seems to have an influence upon the length of time blood can be successfully stored.

The publication of Rachel Carson's *Silent Spring* has focussed attention on the dangers of pesticides. Activation analysis permits agricultural scientists to detect pesticides on crops and in prepared foods by monitoring traces of bromine and chlorine that are left on the foods, even after processing.

Activation analysis not only identifies dangerous chemical culprits in biology, but it can also exonerate elements under suspicion. For example, it was thought for some time that trace amounts of selenium in peas caused a muscular paralysis called "lathyrism" in underfed parts of the world where peas are a main source of food. Kenneth P. McConnell, at the University of Louisville, has shown through activation analysis that selenium is not guilty. The cause of lathyrism has recently been shown to be a copper deficiency induced by beta-aminopropionitrile (BAPN) present in two varieties of peas.

Another biological application, this time with underworld overtones, is the use of activation analysis to identify the geographical source of opium. George W. Leddicotte, one of the pioneers in activation analysis, showed at Oak Ridge National Laboratory that this could be done by identifying the trace elements the poppy plants absorb from the different soils in which they are grown around the world.

A NEW TOOL FOR GEOLOGISTS

The lunar rocks aren't the only mineral targets of activation analysis. There are many rocks on the earth's surface that reveal their minor constituents to the geologist when irradiated with neutrons. There are also meteorites that bring us direct knowledge about the occurrence of elements in the cosmos.

A basic problem in cosmology is to estimate the relative abundances of the chemical elements throughout the solar system and the rest of the universe. An astronomer can tell what the incandescent stars are made of by using his

spectroscope, but the composition of colder bodies in the reaches of outer space is practically unknown. Careful analysis of those extraterrestrial messengers, the meteorites, is the best source of firsthand data from outside our atmosphere.

Using activation analysis, scientists have studied the relative abundances of the "rare-earth" elements in a number of meteorites. The rare earths all have similar chemical properties and are supposed to have evolved as a unit throughout the history of the cosmos. Any differences observed between terrestrial and meteoric rare-earth abundances will call for a special explanation.

Scientists have also compared the rare-earth abundances in terrestrial sediments with those in chondrites, the common stony meteorites that are supposed to be the best representatives of extraterrestrial matter. Their results show that the earth's crust tends to be richer than meteorites in the lighter rare earths. A study of the evolution of the earth's crust indicates that this actually should be the case, affirming the consistency of geological and cosmological models.

One problem in petroleum geology, that of cheaply and quickly analyzing hundreds of rock samples for lithium, beryllium, boron, carbon, and other light elements, is solved by activation analysis using charged particles such as protons and deuterons. In this application activation analysis supplements X-ray fluorescence, another test procedure, which is not applicable in the very low end of the periodic table.

A VERSATILE TOOL

Only a few of the manifold possible uses of activation analysis have been mentioned in this section. Other, perhaps less exciting, examples, such as macroanalysis, impurity control in semiconductor manufacturing, and the measurements of contaminants in chemical plants, could also have been mentioned. Moreover, this new method has just begun to prove its usefulness to science and industry, so that new applications can be expected over the next several years.

SOME TECHNICAL CONSIDERATIONS

ACTIVATION ANALYSIS PRINCIPLES

We have already pointed out that the first step in any activation analysis is the choice of the best nuclear reaction. The best reaction is determined not only by the nuclear properties of the element to be detected but also by the kind of bombarding particle we choose. The nuclear properties of the element are, of course, fixed, but the research worker may choose the particle source and energy. Consider the many nuclear reactions that can be made to occur:

TYPE OF PARTICLE	AVAILABLE REACTIONS*
Thermal neutrons (velocities around 2200 meters/sec)	(n,γ) = (thermal neutron in, gamma ray out)
Fast neutrons (velocities close to that of light)	(n,2n), (n,γ), (n,p), (n,α)
Charged particles	(p,n), (p,d), (p,γ), (d,n), (d,p)
Electromagnetic radiation	(γ,n), (γ,p), (γ,d)

*n = neutron, p = proton, d = deuteron, α = alpha particle, γ = gamma ray.

Despite this tempting smorgasbord of reactions, most activation analysis is done with thermal neutrons, mainly because they are easy to get in quantity and because they react with many nuclei in the periodic table. Fast neutrons are the next most popular.

The desired nuclear reaction will take place at a rate proportional to the neutron flux (the number of neutrons passing through a square centimeter each second) and the nuclear cross section. A simple equation describes the process:

$$R^+ = \phi\sigma N$$

where R^+ = the number of atoms activated per second in each cubic centimeter of the target
ϕ = the neutron flux, in neutrons/cm^2-sec
σ = the reaction cross section, in cm^2
N = the number of target atoms/cm^3 in the sample

The total number of radioactive atoms produced after a time, t, is just the product R^+t. Even as the desired radioactive atoms are being created, they are also decaying and being lost. The rate of decay is given by:

$$R^- = \lambda N^*$$

where λ = the radioactive decay constant, which is equal to 0.693 divided by the half-life
N^* = the number of radioactive atoms/cm^3

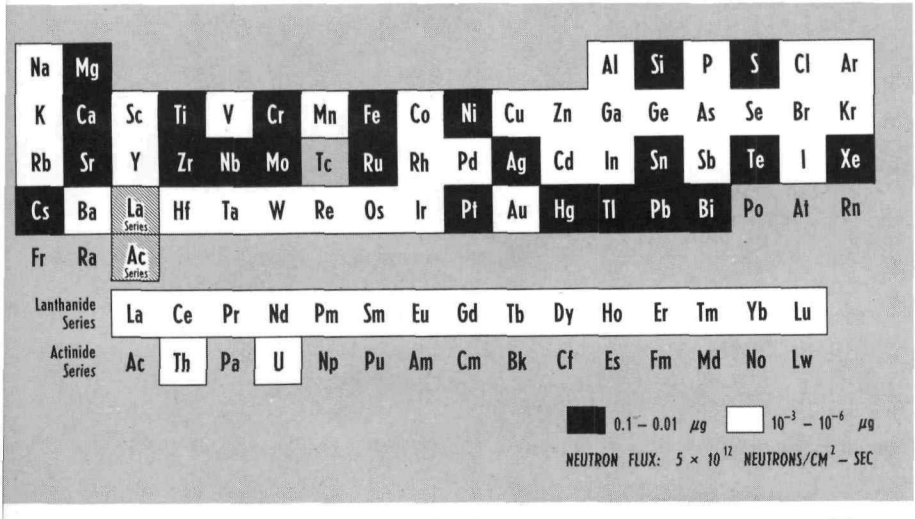
If new radioactive atoms are being born at a constant rate, the number of them in the sample will keep increasing until their rate of formation just equals their rate of decay, or $R^+ = R^-$. Usually it takes too long to get to this point, which is called equilibrium, and the experimenter settles for fewer radioactive atoms than he could get if he wished to wait for the additional irradiation. Of course, if the atom's half-life is short, on the order of minutes, equilibrium can be reached rather easily. But then by the time the irradiated sample has been transferred to the gamma-ray counter, almost all the desired atoms will have decayed. Some compromise between irradiation time and neutron-flux level must be reached. Both time and flux cost money. The experimenter must choose the combination that costs him the least and still gets the job done.

However, all this talk about reducing costs is academic if the cross section, σ, is so small that we cannot create enough radioactive atoms to identify the elements in the sample. The reaction cross section is set by nature and does not recognize financial incentives. In some elements, it is so small that no reasonable amounts of flux and time

will give us enough activated atoms for analysis. Helium, nitrogen, oxygen, silicon, and other light elements have such very low thermal-neutron-activation cross sections.

The sensitivity of activation analysis in detecting small quantities of elements varies from element to element as their cross sections vary. Sensitivity also depends upon the type and quantity of bombarding particles. The accompanying figure showing the periodic table may be thought of as the surface of some planet that we are trying to map with the aid of a telescope. A telescope with a certain magnification permits us to see the picture shown. Some elements stand out vividly, some are less distinct, some are altogether invisible. Suppose we increase the magnification? This is akin to increasing the irradiating flux, the irradiation time, or both. More elements will then become visible

DETECTION SENSITIVITY
FOR ELEMENTS IN THE PERIODIC TABLE



Elements shown on white background are readily detected by activation analysis. Those shown on black are only detectable if present in higher concentrations as indicated in the legend (μg = microgram). The detection of elements shown on gray is not practical. Higher fluxes or longer irradiation times would increase the detection sensitivity.

in the picture. Conversely, reducing the magnification causes the picture to become more blurred, with some elements dropping out of sight completely.

This optical analogy can be carried a step further. When Mars is photographed in ultraviolet light new features, unseen with visible light, reveal themselves. This effect is duplicated in activation analysis by changing from thermal neutrons to fast neutrons, or from neutrons to protons. The nuclear cross sections change radically with such a switch, and new elements become visible to the analyst.

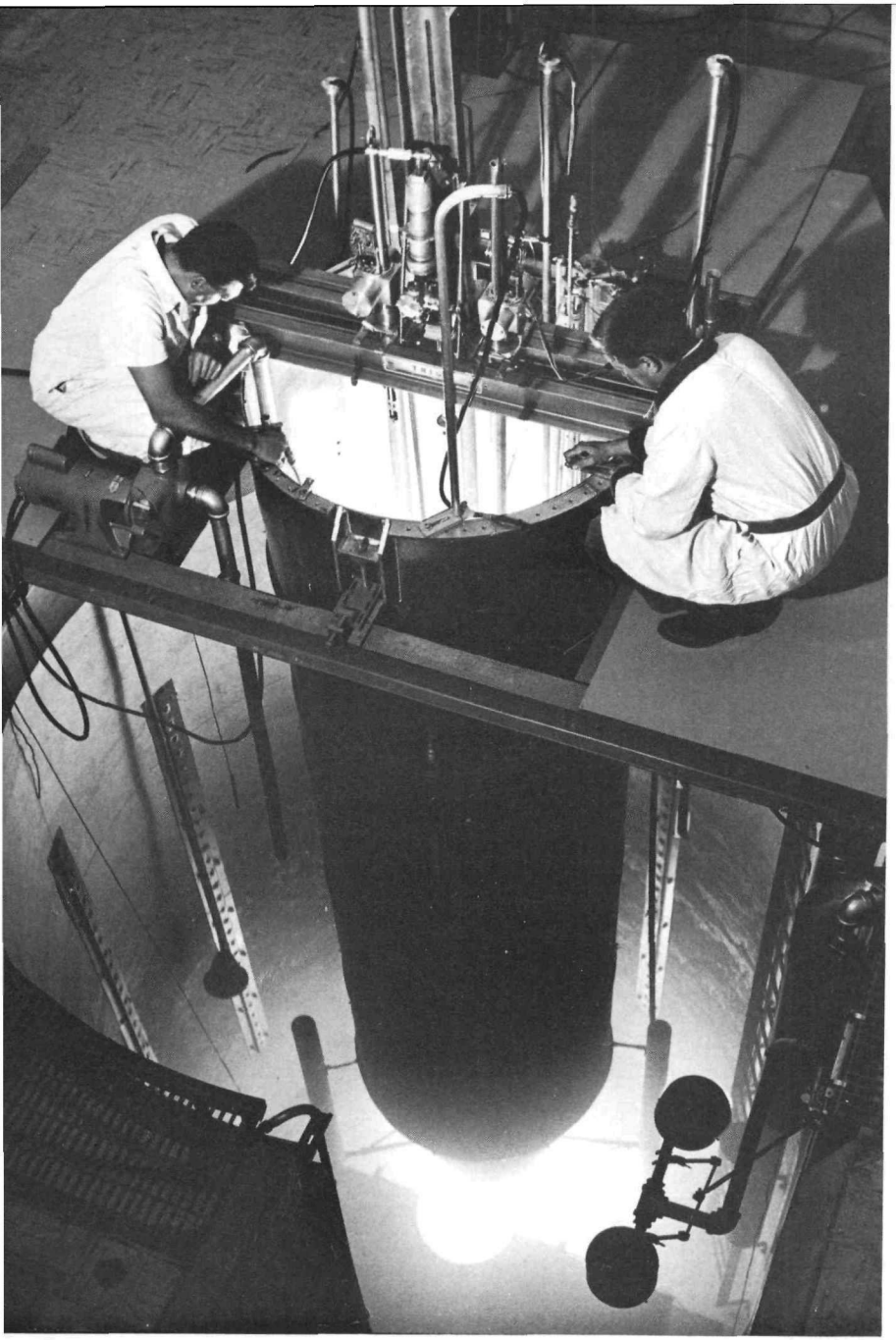
By probing the unknown sample with different particles at different energies and by varying fluxes and irradiation times, scientists have found that nearly all the elements in the periodic table become visible through activation analysis. It is this ability to vary techniques which makes activation analysis such a flexible tool.

NUCLEAR MACHINES

Neutrons are the best activating particles for most applications. Being electrically neutral, they invade the nuclear domain easily.

The neutron source with the greatest flux is the nuclear reactor. Fluxes up to 10^{15} neutrons/cm^2-sec are possible. In a thermal reactor, which means just about all existing reactors, the neutrons zip around with an average velocity of 2200 meters/sec and are in thermal equilibrium with the atoms in the surrounding nuclear fuel. Fast neutrons are produced in the fission, but they are rapidly slowed down by collisions with atoms in the reactor. A few experimental reactors operate with fast neutrons, but there are more convenient sources of fast neutrons. They are described below.

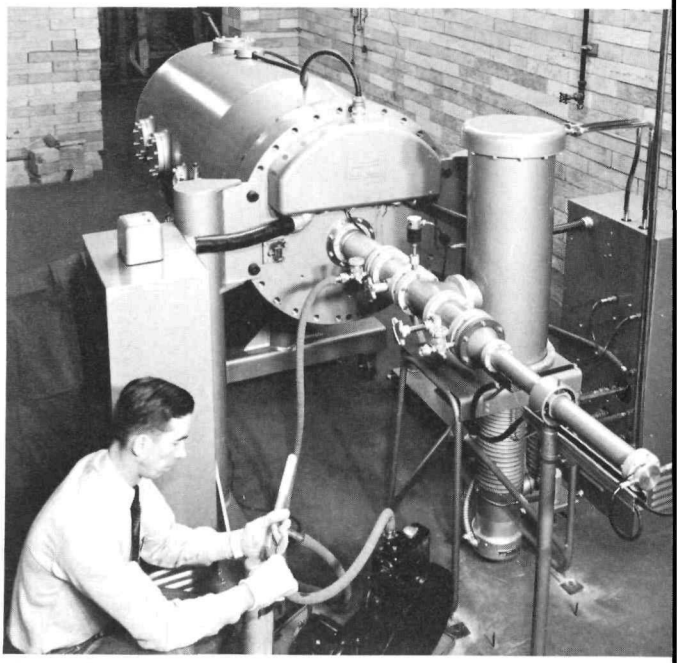
Research reactors produce thermal-neutron fluxes of 10^{12} to 10^{13} neutrons/cm^2-sec. An important characteristic of these reactors is the easy access to the neutrons in the core. Tubes permit samples to be inserted into the core and withdrawn at the pleasure of the experimenter without affecting other research work being carried out with the reactor. Some of the tubes are a high-speed pneumatic variety much like those used in some department stores.



TRIGA reactor during a controlled pulse of radiation. Activation analysis samples can be inserted directly into the core of the reactor.

Courtesy General Atomic.

NEUTRON SOURCES



A Van de Graaff generator. The charged particles are separated from their electrons in the large tank by a moving belt. The charged particles are then accelerated by the high voltages that have built up and emerge from the tank through the long tube.

Courtesy High Voltage Engineering Corporation.

A neutron howitzer. An alpha-emitting radioisotope mixed with beryllium generates neutrons for activation analysis experiments. Most of the volume in the container is occupied by shielding.

Courtesy Nuclear Materials and Equipment Corporation.

They whisk irradiation samples in and out of the reactor in little containers which, because of the speed at which they travel, are called "rabbits." Speed is essential when short-lived radioisotopes must be counted quickly before they disappear.*

A second important source of neutrons is the electrostatic particle accelerator. It employs high voltages to accelerate charged particles down a tube. The high-speed, charged particles can be used for activation directly or, as is more usual, they can be directed into a special target which produces neutrons through (p,n), (d,n), or (α,n) reactions. The neutrons created in this way then bombard the sample. The moon crust experiment described earlier uses the (d,n) reaction with a tritium target to produce very fast, 14-Mev neutrons. Fast neutrons can be slowed down if desired by placing a block of moderating material, often beryllium, graphite, or paraffin, in the path of the beam. Neutron–atom collisions inside the block will slow the neutrons quickly. Fast-neutron fluxes of 10^8 neutrons/cm^2-sec can be generated by commercially available accelerators, like the Van de Graaff machine that is illustrated. Cockcroft-Walton machines are also often used for activation analysis. Both types of accelerators can also be employed in other kinds of nuclear research.

The simplest neutron generators are the isotopic sources, sometimes called "neutron howitzers." The neutrons are created in the (α,n) reactions that occur in a carefully prepared mixture of beryllium and an alpha emitter like polonium-210 or plutonium-238. The neutron howitzer is simply a well-shielded container for the fuel with an access hole for the sample to be irradiated.

As noted earlier, the cost of the neutron flux is important to any activation analyst. The neutron fluxes produced by the electrostatic accelerators are several orders of magnitude lower than those available in reactors, but this is offset by their lower costs. A research reactor with a flux of about 10^{11} neutrons/cm^2-sec has a price tag around $150,000. A particle accelerator capable of generating a neutron flux of

*For more information on these machines, see *Research Reactors* and *Accelerators*, companion booklets in this series.

10^8 neutrons/cm^2-sec costs about $15,000. Cheapest of all are the neutron howitzers. A flux of 10^4 neutrons/cm^2-sec, representing a five-curie* alpha source, will cost only about $2000.

Low costs are appealing, but higher fluxes increase the sensitivity of the activation analysis. Consequently, isotopic sources are employed only when special, high-cross-section elements are in the sample.

COUNTING AND MEASURING

After the atoms being analyzed have been made radioactive by the bombarding particles, their fingerprints must be taken. What's more, they must be taken in a hurry, for the activated atoms are decaying.

The sample is counted by surrounding it with scintillation crystals, which emit flashes of light, or scintillations, each time a gamma ray passes through them. The flashes are detected by photomultiplier tubes that convert them into pulses of electricity. The brighter the flash, the more energetic the gamma ray, and the higher the voltage of the electrical pulse. The faster the activated atoms decay, the faster the decrease in counting rate.

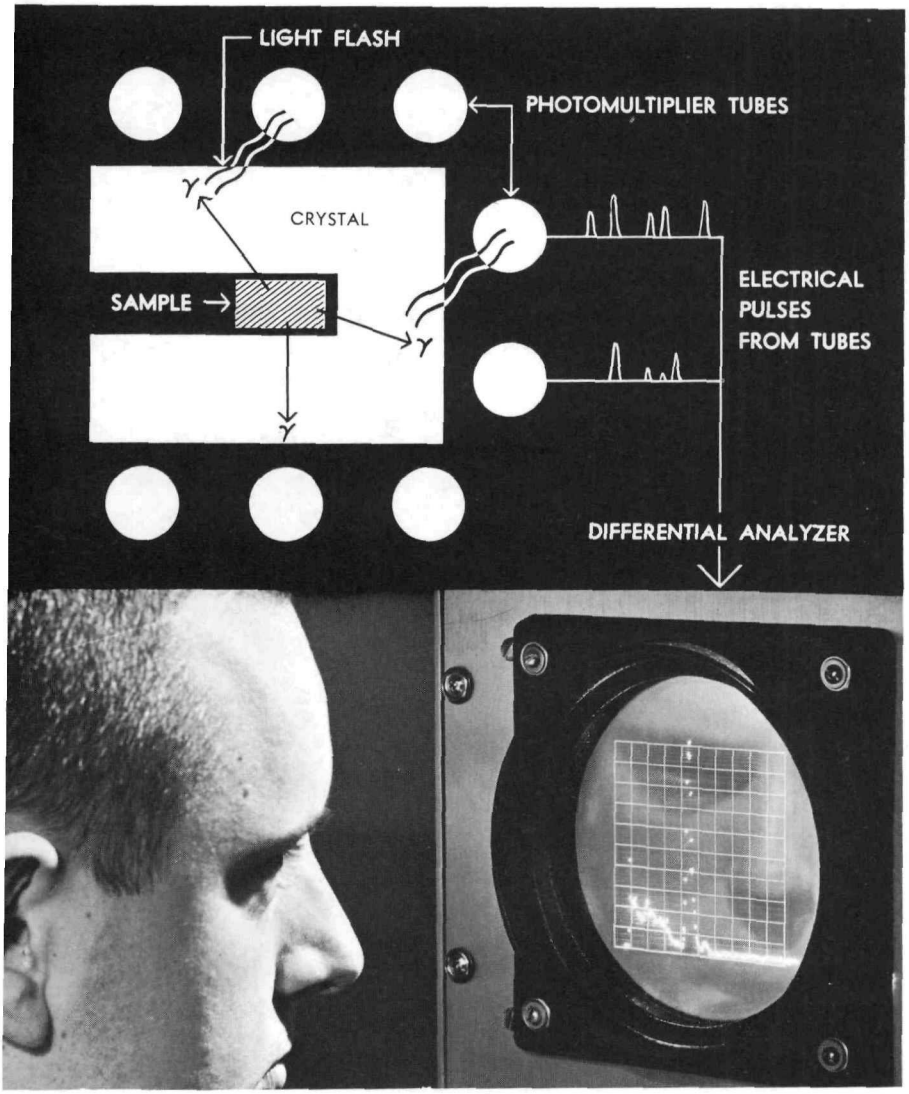
DATA PROCESSING

In a typical activation analysis, hundreds of electrical pulses with varying voltages come flooding out of the counting device each second. A rapid electronic computer is needed to sort them out and make sense from them. This computer is called a multichannel differential analyzer. It is a mass of wires and transistors that first separates the pulses and sorts them into different bins: a bin for those with energies between 1.0 and 1.1 Mev, another for 1.1 to 1.2 Mev, and so on. Each bin corresponds to a different channel in the analyzer.

The machine also totals up the number of pulses in each bin and displays the results to the operator as a graph drawn

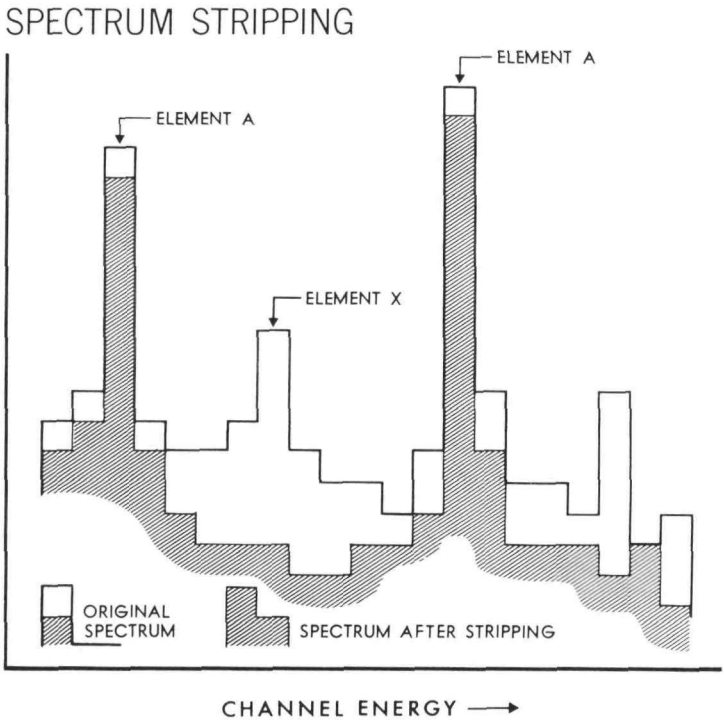
*A curie is a unit of the intensity of radioactivity in a sample of material. One curie equals 37 billion disintegrations per second.

COUNTING AN ACTIVATED SAMPLE



Activation analysis sample being counted. Gamma rays cause light flashes in crystal, which are turned into electrical pulses by photomultiplier tubes. Pulses are added by energies in a differential analyzer, and the results projected on the screen. The oscilloscope on a differential analyzer indicates the number of gamma rays accumulated in each energy range channel.

Courtesy General Atomic.



Graph shows gamma rays accumulated by differential analyzer for elements A and X. By subtracting characteristics of element X, graph for element A becomes clearer. Shaded area is what remains after the effect of element X is stripped out.

electronically on the face of an oscilloscope. The graphs are made up of little steps, one step for each energy bin. Wherever the experimenter finds a bin with a lot of pulses accumulated, he knows that the irradiated sample is emitting many gamma rays with the energy shown on the bin label.

Since each radioactive atom in the sample has a different half-life and its own private set of gamma rays, the graph presented by the differential analyzer is really the sum of all the fingerprints of all the elements in the sample. Although some peaks in the graph may be easily associated with certain elements, two fingerprints on top of one another may make a smudge that is difficult to unravel.

Some clever solutions have been found to this problem. Suppose that we know that element X is in the sample and

we also know its fingerprint. We can instruct a computer to automatically erase the fingerprint of X from the graph. When the pulses due to element X are subtracted, the resulting graph is less confusing. Additional elements can also be removed from the graph by the computer if desired. Remaining elements then begin to stand out and can be identified by using a table of gamma-ray energies. This practice of subtracting the fingerprints of known elements is called *spectrum stripping.*

Another technique, which has similar effects, is to allow short-lived radioactive elements in the sample to decay before beginning the counting process. If counting is delayed just half an hour, for example, many interfering elements can be eliminated without resorting to spectrum stripping. It is also possible to keep certain elements from getting activated enough to cause interference by cutting the irradiation time.

Of course, interfering elements can always be removed by chemical separation prior to activation analysis. This technique is widely used and is very effective. Indeed the question of whether or not to use chemical separation permits us to distinguish two schools of thought in activation analysis. On one hand we have a school which uses fast, carefully planned irradiation, along with chemical separation, and then the application of highly automated counting and computing equipment. The other school practices what is called "instrumental activation analysis," which cold-shoulders chemical separation and relies completely upon irradiation, counting, and computing. The latter approach is fast and clean; the former is more flexible and often more sensitive. Each has its place.

Automatic data processing, regardless of the school that uses it, is an important key to bringing activation analysis out of the curiosity stage and making it a fast, versatile, routine analytical tool.*

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*An automated activation analysis system, coupled directly to a nuclear reactor activating source and a digital computer, could analyze thousands of samples per day with only technicians in attendance. Such a project is being developed by Dr. Richard E. Wainerdi of Texas A. & M. College under the sponsorship of the Atomic Energy Commission.

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MOTION PICTURES

Available for loan without charge from the AEC Headquarters Film Library, Division of Public Information, U. S. Atomic Energy Commission, Washington, D. C., and from other AEC film libraries.

Neutron Activation Analysis, 40 minutes, sound, color, 1964. Produced for the Atomic Energy Commission by General Atomic Division, General Dynamics. This professional-level motion picture deals with the nature, potentialities, and applications of neutron activation analysis.

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Printed in the United States of America

USAEC Division of Technical Information Extension, Oak Ridge, Tennessee

June 1968