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Report on

A Method for Locating Cracks and Faults

in Metallic Structural Members and Machine Parts

by

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BELLEVUE, D. C.

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NAVY DEPARTMENT

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Report on

A Method for Locating Cracks and Faults in Metallic Structural Members and Machine Parts

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Table of Contents

ABSTRACT

The problem of revealing flaws in metal structural members and machine parts is reviewed in general and the possible development of a new technique based on radioactivity is discussed. Recent original research on this subject is included.

INTRODUCTION

(a) Authorization

1. This work was authorized by Bureau of Aeronautics letter Aer-E-252-FAM L5-2(1) JJ46-1 of 14 September 1936, with Bureau of Engineering first endorsement JJ46-1/L5(6-9-Ds) thereto, of 17 September 1936.

(b) Statement of Problem

2. The problem stated in general terms is to find a suitable method or set of methods whereby flaws produced in non-magnetic materials and parts, by the processes of fabrication or by use in service, may be advantageously revealed. Materials and parts of particular interest are those in use on aircraft where the presence of faults is a very serious matter.

(c) Known Facts Bearing on the Problem

3. It is well to review at this point methods that may be applied to this problem. Many kinds of tests have been described in both engineering and patent literature, but they may be divided into several groups.

(1) Radiographic methods. When the defects are large, such as large internal porosities and cracks, X-ray and gamma radiography may be employed. Unfortunately, in the present state of development, neither X-rays or gamma rays can reveal very fine cracks.

(2) Surface examination. It is possible to find exceedingly fine surface defects by suitable preparation and examination (by microscope if necessary) of the surface of the test object. The disadvantages of this method are that only defects that reach the surface are revealed and that it gives no good indication of the importance of any observed defect.

(3) Electric current methods. When a steady current is passed through a test piece, the current distributes itself through the piece in accordance to the resistance characteristics of the various portions of the test object. The nature of the flow lines near the surface of an object may be revealed by a plot of the equi-potential lines as determined by probe tests on the surface. Voids and fissures near the surface may cause a disturbance of the pattern of flow lines. Disadvantages of this method are that the method is exacting and laborious to follow.

(4) Thermal methods. Heat flows according to laws similar to those governing the flow of electric current. Thus, the principles of method (3) are used, the recorded potentials are now temperatures, and the distortions in the temperature field plots are taken as indicative of the possible existence of faults. This type of method is even more involved in its application than method (3).

(5) Magnetic and electromagnetic methods. Magnetic power methods of revealing defects such as the "magnaflux method" have become popular and much used in the testing of steel and iron parts, but unfortunately these cannot

be applied to non-magnetic materials. For these materials, electromagnetic methods must be resorted to. As mentioned before, the current distribution in a test piece may be modified by the presence of cracks and flaws and the attendant magnetic field of the current through the test piece might also show irregularities. The chief difficulty in this idea is that even with strong currents through the test piece, the circular field strength is of the order of a few gauss and the difficulty of showing small irregularities in such weak fields is not easily surmounted. Eddy currents are induced in all metallic conductors when placed in a changing magnetic field. The course of these currents will be altered by voids and fissures with an attendant change in the counter-field set-up by the eddy currents. If means can be developed to make full use of this principle, this method should have considerable use.

(6) Other methods. There are various methods that cannot be classed under any of the preceding groups. Among these methods are sonic methods, destructive performance tests, in which a group of parts is judged by the performance of randomly chosen parts, and so on. This report deals with a method which seems to have enough advantages and possibilities to be worth developing.

(d) Basic Idea and Theoretical Considerations

4. It has occurred to the writer that radioactivity might be employed if means are developed for introducing radioactive material into the flaws and porosities of the metal piece under test. The first possibility that came to mind was the diffusion of gases through metals. At elevated temperatures this diffusion proceeds readily and a test piece enclosed in a chamber containing radon or thoron, which are gaseous radioactive emanations, would absorb the gas, proceeding most rapidly where the porosity is greatest.

5. Once within the metal and in greatest concentration at points where faults have provided space for collection, the radioactive material is in a position to indicate by its radiations the location of fissures and pockets. This may be done by photographic material around the test piece if there is sufficient time to await results or by the more sensitive electrical detection apparatus employing ionization chambers and tube counters. The above method, however, has serious drawbacks in that it is not easily done, that it is likely to be very expensive, and also that there will be considerable danger to the operators from the gaseous radioactive material.

6. An alternative possibility which does not have these disadvantages, but is more limited in application is the use of radioactive liquids which get into surface cracks readily enough and perhaps even into the metal via porous channels if sufficient hydrostatic pressure be applied. (The example of "sweating" water through brass valve castings may bear this out.)

7. The feasibility of the latter method depends upon how powerful a liquid or fluid source can be made and also if satisfactory diffusion into crevices and porosities will take place. While it may be unable to locate isolated blow holes, such defects are better located by radiography anyway, and this method should be looked upon as a supplementary rather than a generally applicable method.

8. The essence of the idea having been set forth, it is now necessary to examine it more critically, putting in whatever scientific facts bearing on this problem that are available.

9. First to be considered is the source of radioactive material to be used in this method. The principal and best known radioactive elements are uranium, radium, and thorium, from which a number of other radioactive materials are formed by natural radioactive disintegration. Uranium salts are weakly radioactive and serve mostly as sources for preparing radium. Radium salt in pure form is a powerful source of radioactive radiations, but is very expensive. Thorium (Th), like uranium, is weakly active but serves as the material for preparation of the powerful mesothorium. Since Th is commercially available in the form of ThO_2 (for refractories and incandescent gas mantles) at fairly reasonable prices, it seems to be the logical radioactive material to employ in a practical test of the described method. Some of the radioactive properties of Th may now be briefly described and the available numerical data be listed.

10. Table I shows the properties of the thorium family given in order of their disintegrations. A study of this table shows that a mass of thorium salt, which is old enough to have present all the decay products, emits several types of radiation: α-particles, β-particles (electrons) and gamma rays. The intensities of these radiations, however, are measured by the amounts of the kind of element producing them, so for the present problem it is of importance to estimate, at least, what we may expect. The bulk of the given material is thorium. This gives off only α-particles of 2.7 cm range and gives off 4.5×10^3 of these a second per gram. However, a gram of Th in equilibrium with all its decay products gives off 2.7×10^4 α-particles a second. (For comparison, 1 gram of radium alone gives off 3.7×10^{10} α-particles and in equilibrium 14.1×10^{10}.) The amount of mesothorium in equilibrium with 1 gram of Th has been found to be about 0.52×10^{-7} grams. The amount of mesothorium produced by one gram of Th per year is around 3 micrograms per kilogram.

11. In respect to α-particle radiation, however, mesothorium is 314 times as active, weight for weight, as radium. The comparison on the basis of gamma rays is more difficult, but gives about the same figure, 300 - 500. MsTh is sold commercially and its stated weight is given as the weight of a gamma-equivalent weight of radium. The amounts of the other active products, which, with the exception of RaTh, have short half-lives, present in one gram of thorium, are also very small. Thoron is a gas which decomposes into the solid ThA, giving the surface it condenses on induced radioactivity.

12. Summarizing the α-ray activity of Th is about 10^{-6} to 10^{-7} of that of radium, gram for gram, depending upon the amount of decay products present. The gamma ray activity is such that 6.85×10^6 grams of Th are gamma equivalent to 1 gram Ra while 19.0×10^6 grams of Th has enough mesothorium in equilibrium to be gamma equivalent to 1 gram of radium. In plain terms, a gram of thorium is roughly equivalent in its radioactivity to a microgram of radium.

13. Having discussed the most readily available radioactive material itself, the next point to be examined is the sensitivity of detection methods. Two methods are in general use for detecting radioactivity: (1) Photography,

(2) Electrical ionization methods. The former is the more desirable in practical use, but usually requires time and is not capable of the high sensitivity obtainable by the electric method.

14. To form an idea of the effectiveness of the photographic method, some figures given by H. Przibram (Mitt.Ra.Inst. 139, Wien Ber. 130 (1921) 27) are listed in Table II. These compare the photographic action of α, β, and gamma-rays and light rays in terms of the energy required to bring about changes in the photographic negative. These figures show that from ten to a hundred times more energy per square centimeter is required for detection of radioactive radiations than for ordinary light, but there are good reasons for this. For example, an α-particle may strike at most four or five silver bromide grains in the emulsion before its energy is absorbed by the gelatin. Without going further into this, the figures indicate reasonable sensitivity for α-particle detection. (Photographic detection of a single α-particle is possible but the negative must be examined by microscope to show the streak produced by the α-particle.) The threshold number of α-particles ($10^6/cm^2$) allows detection of fairly small quantities of radioactive material if reasonable time for exposure is available. For a concrete illustration, 1 gram of Th gives out 10^4 α-particles a second. A microgram will give 10^{-2} particles a second or only one in a hundred seconds. Suppose, however, all the particles from this minute amount pass into 1 square millimeter of photographic film for ten days, or about 8.6×10^5 seconds. The number of particles is 8.6×10^3 and their number per square centimeter 0.86×10^6, which is just on the quoted threshold value. If the figures are correct, such small amounts as one millionth of a gram of radioactive material are photographically detectable due to their α-rays. If the radioactive material is carried in water or an oil in such concentration that there are 100 mg/cc, the volume occupied by the radioactive material, one microgram in weight, is 10^{-5} cm^3 or 0.01 cubic millimeter. This is about the volume of a fissure 0.01 mm wide, 1 mm long, and 1 mm deep, a crack of the type sometimes appearing between grains in photomicrographs.

15. It is not likely that the full theoretical capability of the photographic method will be realized in practice, but even if the method is less sensitive by a factor of ten or a hundred, the method will still suffice to show up large surface cracks such as are revealed in "Magnaflux" testing.

16. The electrical method has some advantages over the photographic method in that it is more sensitive and requires less time to make a test. On the other hand, it has some drawbacks which will be mentioned in the following discussion.

17. The electrical method of detecting radioactive radiation is based on measurement of the amount of ionization or electrical dissociation of the atoms or molecules of air or other gas through which the radiation passes. The ionization of the gas allows the passage of an electrical current between electrodes placed in the ionized gas and the magnitude of this ionization current is a measure of the ionization produced and thus a measure of the intensity of the radiation producing the ionization. Early workers measured the ionization by means of an electroscope since its rate of discharge measures the ionization leakage current. More modern methods possessing greater

sensitivity employ ionization chambers which are essentially gas filled chambers containing a pair of electrodes kept at some high, steady d-c potential (usually 500 - 2,000 volts). Any ionization produced in the chamber then causes a current to flow between the electrodes. The current is measured by some sensitive device such as an electrometer or a vacuum tube amplifier system. Apparatus of this type possess high sensitivity and are capable of recording the ionization produced by a single α-particle. Since 1 gram of thorium gives off about 10^4 α-particles per second, a microgram will give off only 1 α-particle in 100 seconds on the average, which is too little for certainty since accidental discharges in the electrometer current occur. However, electrons and gamma-radiation are also being emitted so that the ionization product is probably more than estimated. Furthermore, if radium is used instead of thorium, which emits 3.7×10^{10} α-particles per second per gram, a thousandth of a microgram will give off about 30 α-particles a second, which should be quite definitely detectable by the electric method.

18. Since it is known that 1 α-particle generates 2.2×10^5 ion pairs, it is easy to estimate the ionization current due to a gram of radium. Since radium emits 3.7×10^{10} α-particles per second, the total number of ion pairs produced is

$$3.7 \times 10^{10} \times 2.2 \times 10^5 = 8.14 \times 10^{15}$$

If each ion carries one electronic charge -

$$= 4.77 \times 10^{-10} \text{ e.s.u.}$$

the ionic current or charge generated per second is -

$$8.14 \times 4.77 \times 10^5 = 3.88 \times 10^6 \text{ e.s.u. per second.}$$

Since one ampere-second or coulomb = 3×10^9 e.s.u., the current in ordinary amperes is 1.29×10^{-3}. The ionization current due to the α-particles of one microgram of radium is thus 1.29×10^{-9} amperes. Modern electric valve and galvanometer circuits can detect currents of 10^{-14} to 10^{-19} amperes. However, many electrical detection devices do not rely on a steady current, but by means of a high potential utilize the small amount of ionization built up by a single α-particle:

$$2.2 \times 10^5 \times 4.77 \times 10^{-10} = 1.05 \times 10^{-4} \text{ e.s.u.}$$

$$= 0.35 \times 10^{-13} \text{ coulombs,}$$

to cause still more ionization by a sort of high tension arc. One form of Geiger α-particle counter works on this principle. Development of Geiger counters has been extensive due to research in radioactivity. A recent type of apparatus which combines a counter and a vacuum tube meter circuit and known as the counting meter indicates directly the average rate of arrival of electrified particles. (N.S.Gringrich, R.B.Evans, and H.E. Edgerton, Rev. Sci.Inst. Vol.7, Dec. 1936, pp.450-456) Counting rates from as low as one per second to several thousand per minute are read directly on a meter and the whole apparatus is portable and suitable for routine determination of amounts of radioactive materials in minerals, organic matter, etc. A device of this type modified for the proposed inspection method should allow detection of quite small defects according to the above considerations.

19. So far no mention of the ionization due to β-particles and gamma rays has been made. However, the ionizations produced by α-particles, β-particles, and gamma rays stand in the ratio $10^4:10^2:1$ so we can safely say the major portion of the ionization produced around radioactive material is due to α-particles.

20. The above discussion has indicated that very small amounts of radioactive material (in the case of radium, a thousandth of a microgram; in the case of thorium, about 0.1 milligram) are detectable directly without need for time as in photography. If there is time for cumulative effect of radioactive radiations, the electrical method is capable of detecting extremely minute amounts of radioactive material.

21. In the above, the theoretical considerations in regard to the radioactive method of inspection have been given. These show that the method might be capable of detecting all sorts of surface defects and possibly internal defects where transfer of radioactive material into the interior can be accomplished.

EXPERIMENTAL WORK

(a) Test of Thorium Oxide as a Radioactive Source

22. The experimental work described in the following pages was started on May 17, 1937, with a rough experimental set-up to test the photographic activity of a sample of thorium oxide of which there was on hand a supply of several pounds. A small thin-walled glass phial containing 8.22 grams of thorium oxide was placed in a light-tight can, as shown in Plate 1(a) and (b), along with a strip of X-ray diffraction film having metal fasteners along its length. This arrangement, while rough, provides a range of source to film distances from almost direct contact to the diameter of the can. Plate 1(c) shows the film obtained with some photographic densities determined at several points along the film. The time of exposure was fifteen days. The film shows considerable density at points near the source, but a slight density which does not change much with distance farther away from the source. The blackening near the source is due mainly to corpuscular radiation such as α- and β-rays having sufficient power to penetrate the thin glass wall. That farther out is due entirely to gamma radiation. This rough preliminary experiment shows that thoria has a very effective action on photographic film at close range and also gives a rough quantitative basis for estimating effects at larger distances.

(b) Production of a Fluid Radioactive Source

23. Unfortunately, thorium oxide is a very insoluble material and to produce from it a fluid radioactive source is difficult. Therefore, the first liquid source experimented with was thorium nitrate solution, since this salt is quite soluble in water.

24. Water has some obvious disadvantages as a fluid vehicle, such as tendency to rust ferrous surfaces and also its suitability as an electrolyte medium in which the dissolved metal ion may be electrochemically displaced. Nevertheless, some preliminary tests were made using thorium nitrate solution as radioactive fluid in location of defects. These will be mentioned again later.

25. Oil, especially a light oil of the penetrating type, seems to be a very desirable vehicle fluid. Some rough attempts to get various thorium salts into oil directly were not successful. Two possibilities, however, are open: (a) Formation of a thorium soap which will dissolve readily in oil, and (b) the formation of a thorium phenyl compound similar to the lead tetraethyl employed in gasoline.

26. The first possibility was tested out by Mr. Singer and the writer. It was found possible to make a thorium soap by adding liquid soap to a thorium nitrate solution at about 50° C; the precipitate or thorium soap was filtered off and dried in an oven at low heat. The dried soap was divided into 0.2 gram samples and numerous experiments were carried out to find a suitable solvent for the soap. Out of some 22 organic solvents tried, the only ones of promise were linseed oil, castor oil, and butyl butyrate, the last being the best. It was also found that the thorium soap solution in butyl butyrate could then be diluted with a light mineral oil known by the trade name "ultrasene."

27. The other possibility of using metal phenyl compounds was not tried due to the lack of available knowledge about the preparation of such compounds. Chemical catalogs were consulted, but no thorium phenyl compounds were listed. This possibility should not be forgotten, however.

28. In view of the fact that a fair quantity of thorium oxide was available, the writer carried out some experiments on making soap solutions from this material instead of the nitrate. Briefly, the oxide was converted to the sulphate by digestion with hot sulfuric acid. The sulphate was dissolved in water and treated with ammonium hydroxide to precipitate thorium hydroxide. From this point the well known procedure of treating a fatty acid with a hydroxide to produce a soap (metallic salt of the fatty acid) was followed. Solutions of stearic and oleic acid were treated with the wet thorium hydroxide. The hot solutions dissolved the hydroxide completely, the oleic acid solution remaining clear at room temperature, the stearic acid freezing as expected. These solutions were then tested for their solubility in light mineral oil (ultrasene) and while both the stearic and oleic acid solutions would dissolve, only the oleic acid solution would remain clear on standing. Experiments to see how great a concentration of thorium can be introduced into mineral oil in this way have not yet been carried out.

(c) Tests of Radioactivity of Solid and Liquid Materials

29. To test the activity of the various materials use was made of a good electroscope of French make, especially designed for testing radioactivity of small objects and small samples of salts or greases and oils. This instrument is shown in Plate 2. The rate of discharge determines the activity of the sample. Table III shows some discharge times for certain radioactive materials worked on. The activity of the thorium soap seems to be quite good, but that of the stearic and oleic acid solutions rather poor. This is to be expected, for the weight concentration of thorium is probably less and the emission of α-particles confined perhaps to the very outside surface layers.

(d) Practical Inspection Tests with Fluid Sources

30. A search for metal specimens having various surface defects which could be used for trying out the radioactive method of inspection gave a piece of bronze stock having bad longitudinal cracks and some zinc plates 1/2 inch thick which had been used in bullet-stopping experiments and were full of cracks of all types and sizes.

(1) Test of radioactive oil as fluid source for showing defects in shattered zinc plate.

The oil solution was made up as follows: 1.99 grams of the thorium soap made as described above were dissolved in 20 cc of butyl butyrate (hot solution). "Ultrasene" oil was then added until a solution was obtained which would remain clear when cooled to room temperature. With a total volume of 150 cc, this solution was clear and flowed freely when lukewarm.

The piece of zinc plate with shatter cracks was placed in the warmed radioactive oil and left there about an hour. The piece was then removed from the oil, its surface rubbed dry, then wiped with an alcohol-soaked cloth and finally rubbed dry again. The piece was then placed in a light-tight can with photographic film as shown in Plate 3, which also shows the radiographic films obtained after an exposure time of about one month. The manner of blackening of the films suggests that the oil does not remain in the cracks but creeps all over the test piece.

31. Experiments using a water solution of thorium nitrate did not give much better results and will not be described here.

32. The next experiments to be described are of a different type. Instead of using a liquid medium for the radioactive source use was made of a grease containing thorium oxide which was introduced into the cracks in the test pieces by means of hydrostatic pressure. Plate 4 shows a pressure vessel suitable for use with small specimens, the radioactive grease (contains 1 gram of thoria per cubic centimeter of petrolatum jelly), and the cassettes used for photography.

33. The test specimens were packed in the pressure cylinder with enough thorium grease to completely cover them, the cylinder was then closed and pressure was applied by means of a bottle of compressed air. A pressure of around 1000 lbs./ sq.in. was allowed to remain in the cylinder for several hours. The test pieces were then removed and their external surfaces thoroughly cleaned with benzene, ether, and a dry cloth.

34. Plates 5 and 6 show two of the specimens and the photographic results of the experiments. The specimens were placed in new light-tight cans with photographic film and the exposures lasted five days. Plate 5 shows the results on a round piece of bronze bar stock. The films, however, were not used bare in this experiment as was done in previous experiments but were wrapped in one thickness of black paper and were backed by lead foil. Results and conclusions from these experiments will be discussed later.

35. In addition to these practical experiments, some experiments were carried out to test the possibilities of improving the photographic activity of the source material. This work is still in progress so it will not be discussed fully in this report. The following facts, however, have been established:

(1) The photographic activity of a thorium powder source may be improved by about 10% (as measured by the increase in density of photographic blackening produced by mixing in with the powder such fluorescent materials as calcium tungstate and barium platino cyanide. (These results apply only to bare film and dry powdered thoria.)

(2) Mixing of thoria into vaseline reduces the activity of the thoria by a large amount (2.75 to 1.50 in photographic density).

(3) Preparations of thorium hydroxide dissolved in oleic and stearic acid as described in previous paper give fairly good photographic densities but their dilutions with "ultrasene" oil are not satisfactory for exposure times as short as a few days.

DISCUSSION AND CONCLUSION

36. The experiments described briefly as possible above may now be reviewed and conclusions given.

(1) The comparatively cheap thorium salts may serve as radioactive material in the proposed method for locating faults. As shown in Plate 1(c) the photographic density obtained using thoria is good when the distance between the source and the film is small which is not an objection in the proposed type of test, where the photographic material will be placed practically directly upon the metal surface to be studied.

(2) Radioactive liquids or plastic sources for indicating the presence of faults may be produced in a number of ways from thorium salts. A concentrated water solution of a radioactive salt is perhaps the simplest, but more desirable for reasons already given, is an oil bearing a radioactive material. Methods for making such oils are described in this report.

(3) Practical experiments have been described in which radioactive fluids were used to show defects in metal pieces. Typical of the results are those shown in Plate 3. The top film Plate 3(e) was placed bare upon the top of the piece to be examined, while the lower film, Plate 3(b) was separated from the piece by a thickness of blotting paper. The upper film shows a large blackened area of about the size of the test piece with no definition of any cracks plainly visible in the piece. The lower film shows a non-uniform blacked area with a small triangular region due to the presence of a small piece of photographic film on the under side of the blotter. These films indicate only that faults may be located in general by use of radioactive fluids but do not indicate the nature or shape of the faults. A possible reason for this may be that the radioactive fluid after its introduction into the crevice or fault "creeps" back onto the surface around the

fault. That this tendency may be more of an advantage than a disadvantage, in case only the approximate location of a defect is desired is readily appreciated since the fluid creeping out to the surface can more effectively act upon the photographic material. Water solutions of radioactive salts such as concentrated solutions of thorium nitrate in water were tried, but it is hard to say whether or not the results were any better than those obtained with oil. In one case individual cracks were shown on a sample but the general contamination of the surface by the water solution gave a dark background.

(4) It was found possible to produce a much stronger detection material by mixing finely ground thoria into vaseline and to introduce this material into the faults of the test piece by means of hydraulic pressure. Photographic film placed on the cleaned surfaces of test pieces located in this way show the cracks themselves reproducing their contours. Plate 5 illustrates this technique, but Plate 6 affords more material for discussion. By comparing the films with the surfaces they were placed upon, several things may be noted:

(a) Plate 6(a) shows distinctly the major cracks visible in Plate 6(b) and closer inspection shows hints of still more. In Plate 6(c) a fine crack is shown as a much broadened streak. However, it cannot be claimed definitely that all existing cracks in the specimen were recorded. Some films obtained on another specimen treated in the same manner failed to show certain cracks while some even finer cracks than those omitted were shown. This indicates that there is occasional failure of a crack receiving an adequate supply of radioactive material. Possible reasons which might be advanced are (a) that the particle size of the thoria used was too large or (b) that the radioactive material was not distributed uniformly enough throughout the grease. It appears likely that the chief source of trouble in the pressure grease method lies in incomplete filling of the cracks.

(5) Still another fact brought out in experiments of the kind shown in Plate 6 is that the bottom film is usually the better film since it is the one backed by lead. It may also be repeated that the film when wrapped in a single layer of black photographic paper is much better than bare film which will usually show a mottled background. The photo-density of some of the film markings in Plates 5 and 6 suggest that the exposure time might be reduced still further to three days or so.

(6) The sensitivity and brevity of the recording can be improved and following are some suggestions toward effecting this improvement:

(a) The fluidity of grease is not increased by pressure so increased fluidity and penetration of the active material can be brought about only by increasing the temperature or by using oil emulsions instead of grease. While it may be suggested that still greater pressures be used to bring about penetration, the increase in rigidity of the material must be considered. The particle size of the thoria grain may be reduced to colloidal dimensions by grinding or by chemical precipitation in the form of hydroxide. This treatment should also bring about uniform distribution of the active centers.

(b) To reduce the time required, the strength of the radioactive material may be increased indefinitely but with an attendant increase in price. A milligram of radium in a liter of fluid would not be any more effective as far as α radiation is concerned as a kilogram of thorium salt mixed into a liter of grease. The cost of the radium would be $20.00, taking its price at $20,000 a gram, while a kilogram of thorium nitrate may be purchased for as little as $6.93 (or even less in bulk)*. However, in certain applications to small objects, a radium solution containing 10 or 100 mg/liter might be well worth the price especially if most of the test material is recoverable. With such concentrated materials, the results shown in Plates 5 and 6 could be obtained in minutes or hours instead of days and perhaps even finer defects could be revealed

(c) Another possibility for improvement lies in development of photographic films better suited for this type of work. It was mentioned earlier in this report that one α-particle strikes only four or five silver grains in the emulsion. It appears therefore that a photographic material like a Schumann plate in which the density of silver particles is vastly increased should be very suited for this work.

37. While the possibilities in the use of electrical detection devices have been indicated in this report, time has not permitted an experimental study of their use. Work is now in progress on improvement of the photographic technique according to the recommendations given above and work will also be carried out to test the possibilities of the electrical methods of ionization detection.

* Best present retail price is $3.15 per lb.

SUMMARY

38. The principle of a method for detecting faults in metals by means of radioactivity is set forth.

39. The theoretical possibilities and limitations of the method are discussed in detail.

40. Practical experiments are described in which this method was tried and the possibilities for still further improvement are pointed out.

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In the course of the work, use was made of the following texts:

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Appendix

Note on Possible Bearing of Recent Advances in Modern Physics on the Material of This Report

In the foregoing only well established facts were used in the discussions, but there have been certain developments in physics which in the course of time may offer greater possibilities for this and many other practical applications of radioactivity.

One of these is the production of artificial radioactive substances like radio-sodium with half-lives varying from a few seconds to several years. The prime factor in this new development has been the invention of apparatus for accelerating ions to great velocities for atomic bombardment of matter. The greatest velocities are obtained at present with an apparatus called a "cyclotron." Cyclotrons of the larger type are very costly and expensive in operation but smaller ones are now being built which are much cheaper in cost and operation. The writer has seen one of this type at Cornell University which was built at a cost of about $1500. This has been used to produce various artificial radioactive substances.

Still other advances in modern physics are the discovery of the neutron (a particle having protonic mass but no electrical charge) and studies on its production and properties. These particles, produced when α-particles or other fast moving ions collide with atoms and disrupt them, arelike thermal molecules at low velocities, but at high velocities, due to their lack of charge can traverse great thicknesses of matter without being stopped. It is not safe to say yet that use will be made of the neutron in radiography but such may not be beyond possibility.

Table I

Radioactive Properties of the Thorium Series

Element	At.Wt.	Half Life T	Radiations	Range in cm of α-particles in air at 15° C 760 mm	Wavelengths of γ-rays X.U.
Thorium Th	232.12	1.65×10^{10} yrs	α	2.90	-
Mesothorium 1 MsTh 1	(228)	6.7 yrs	β	-	-
Mesothorium 2 MsTh 2	(228)	6.13 hrs	β, γ	-	12.7 - 212
Radiothorium RdTh	(228)	1.90 yrs.	α,β	4.019	-
Thorium X ThX	(224)	3.14 days	α	4.354	-
Thoron Tn	(220)	54.5 sec.	α	5.063	-
Thorium A ThA	(216)	0.145 sec.	α	5.683	-
Thorium B ThB	(212)	10.6 hrs.	β, γ	-	40.9 - 51.2
Thorium C ThC	(212)	0.5 min.	α,β	4.787	-
Thorium C' ThC'	(212)	10^{-11} sec.	α	8.617	-
Thorium C" ThC"	(208)	3.20 min.	β, γ	-	4.66 - 303
Thorium D ThD	207.77	Stable	-	-	-

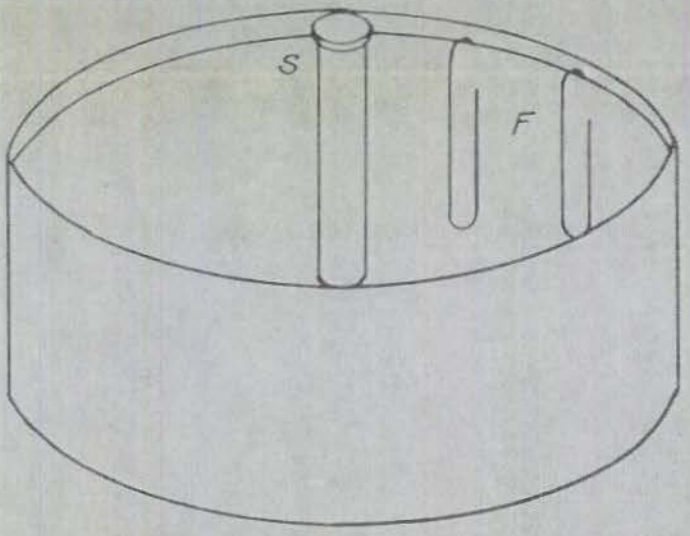
Table II

Nature of Action	α-Rays: No. particles per cm^2	α-Rays: Energy/cm^2 ergs	β, γ-rays Energy ergs/cm^2	Light ergs/cm^2
Photographic threshold	$0.7\text{-}3.5 \times 10^6$	5.7-29	-	0.20
Satisfactory blackening	2.4×10^{11}	2×10^6	10^{10}	$0.7\text{-}2.3 \times 10^4$
Incipient overexposure	8×10^{11}	6.6×10^6	10^{10}	10^9
Complete overexposure	2.6×10^{12}	2.1×10^7	-	-
Negative reversal	4.7×10^{12}	3.9×10^7	-	-

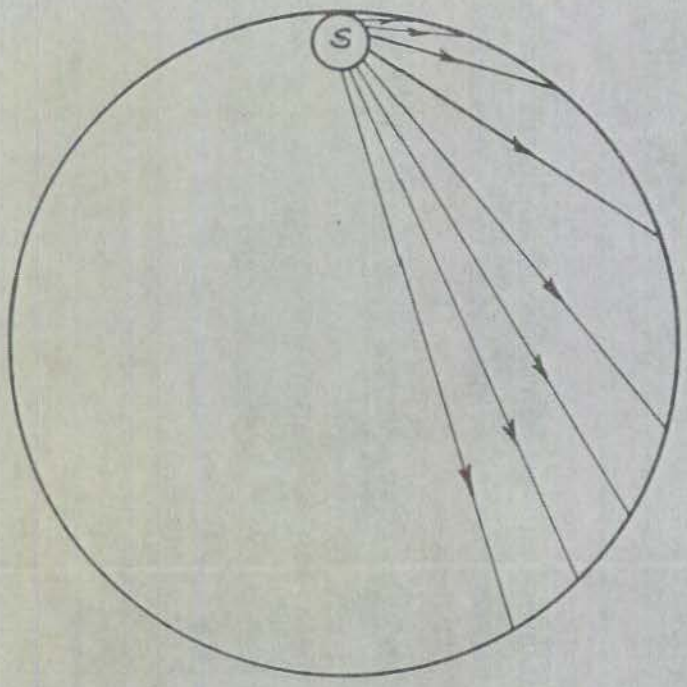
Table III

Material (1 g. sample)	Mean Decay Time*	Notes
Thorium oxide	1 min. 5 sec.	(old stock)
Thorium soap	3 min.25 sec.	1 mo. after preparation.
Thorium hydroxide	2 min.48 sec.	1 week after preparation.
Conc. solution of thorium hydroxide in stearic acid.	44 min.31 sec.	Freshly prepared.
Conc. solution of thorium hydroxide in oleic acid.	69 min.	" "
Blank test	104 min.	

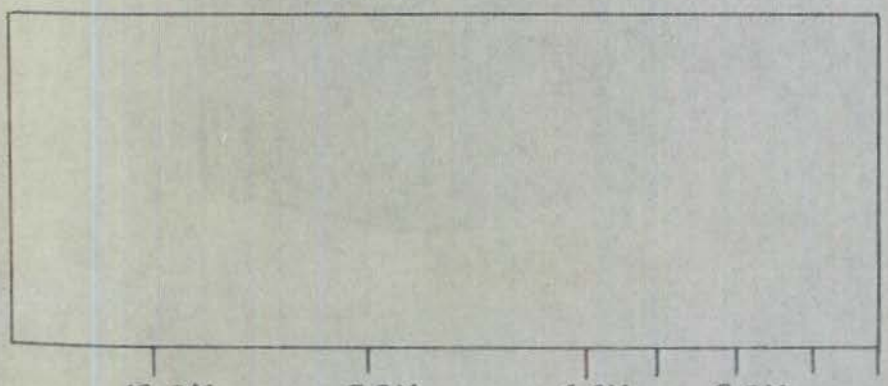
*Over the arbitrary 100 sec. U scale of instrument.



(a)
S: SOURCE
F: FILM



(b)
RANGE OF
SOURCE TO FILM
DISTANCES



(c)

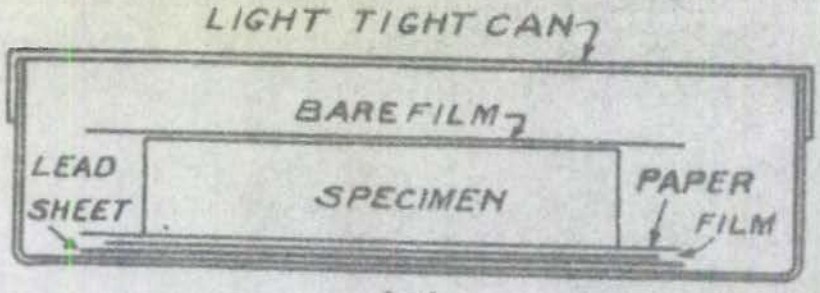
10 CM. 7 CM. 4 CM. 2 CM. DISTANCES
0.9 0.90-.98 1.07 1.62 DENSITIES
DENSITY UNEXPOSED BACKGROUND = 0.74

PLATE 1

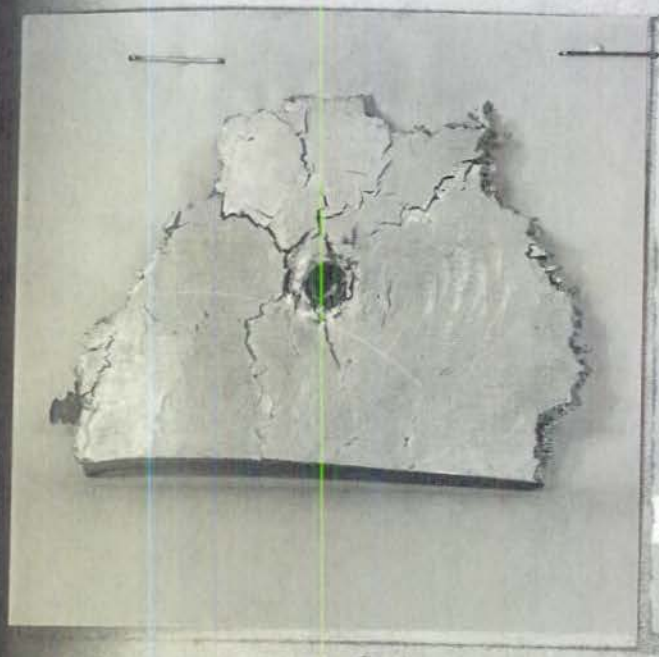
PLATE 2

(c) (e)

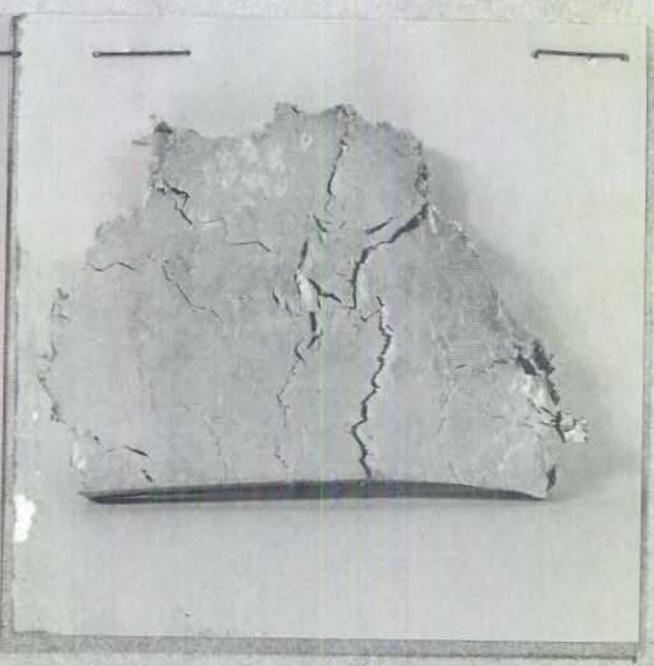
PLATE 3



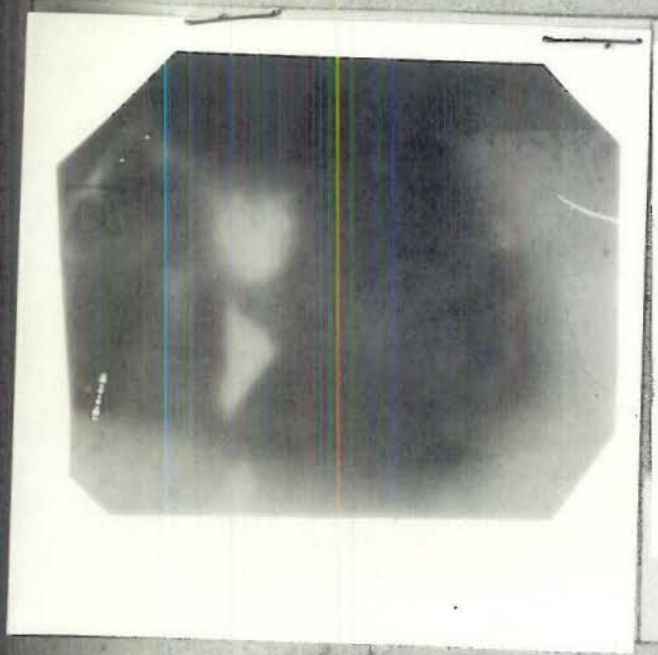
(a)



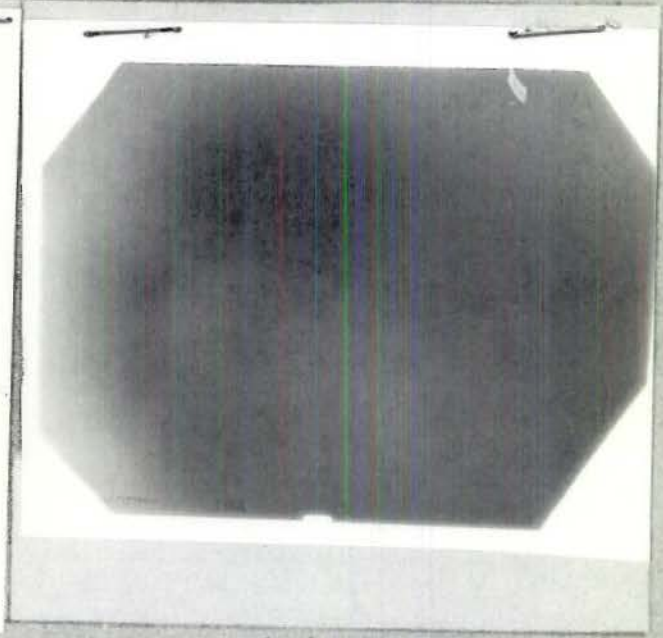
(b)



(d)



(c)



(e)

PLATE 3

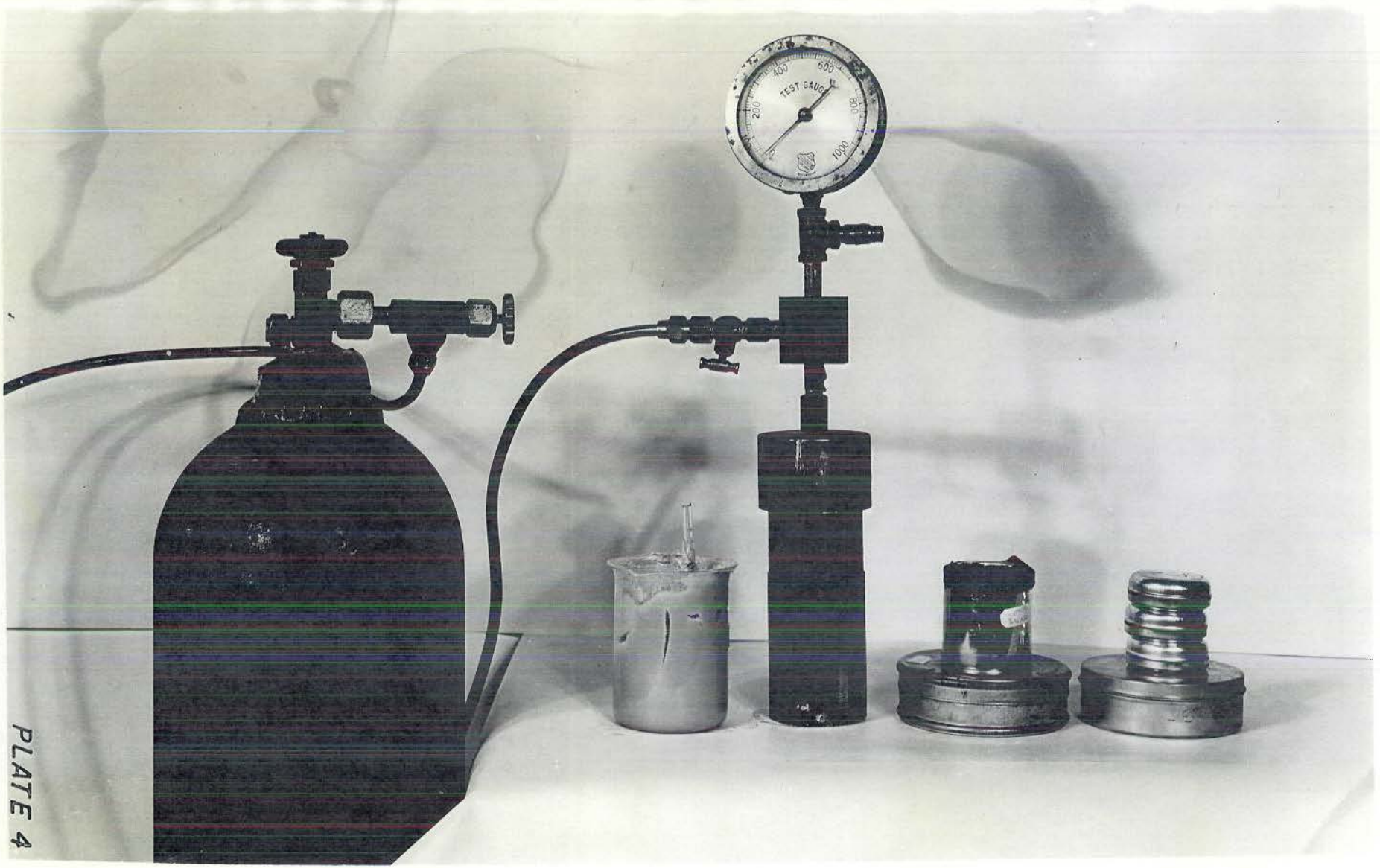
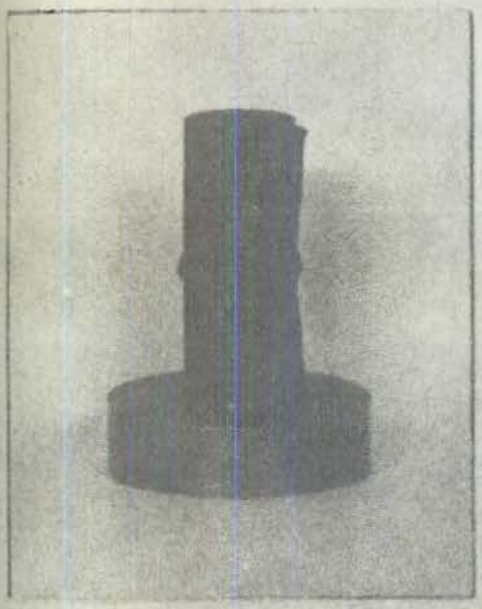
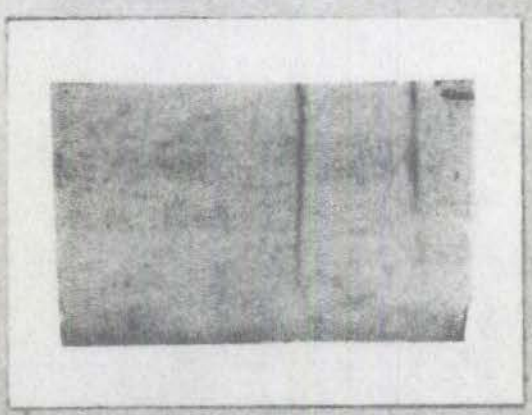


PLATE 4

(a)



(b)



(c)

PLATE 5