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TWO NEW METHODS TO INCREASE THE CONTRAST OF TRACK-ETCH NEUTRON RADIOGRAPHS

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ABSTRACT

Two new methods for increasing the contrast (optical density span) of track-etch neutron radiographs were evaluated. In one method fluorescent dye was deposited in the tracks of the radiograph. The radiograph was then examined under ultraviolet light. The second method was a crossed polaroid filter technique. The radiograph was placed between crossed polaroid filters and then illuminated with a diffuse white-light source. An increase in the optical density span from .10 to .37 was obtained with the dye method. With the polaroid method, the increase obtained was from .10 to 2.4.

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SUMMARY

Track-etching is one of several methods used for the recording of neutron radiographs. The method consists of placing a piece of clear insulator (track recording) material next to a converter screen, behind the subject in a neutron beam. Neutrons striking the converter cause ions to be emitted. These ions penetrate the clear track recorder material where they cause structural damage. The track recorder is then etched in a suitable reagent. The etching process selectively removes material from the damaged areas leaving a pit or track. The combination of millions of these tracks in the recorder make up the track-etch neutron radiograph. The track-etch method yields a high quality radiograph with one exception: It has poor contrast. The optical density range of a typical track-etch neutron radiograph is of the order of .05 to .10.

This paper describes two new methods for increasing the contrast of track-etch neutron radiographs. In one method a fluorescent dye is deposited into the tracks of the radiograph. The radiograph is then illuminated by ultra-violet light which causes the dye to fluoresce. The fluorescing radiograph is then photographed. The second technique discussed involves placing the track-etch radiograph between crossed polaroid filters and projecting the image onto photographic film. In the untracked areas of the radiograph, the polaroid filters block the transmission of light. In the tracked areas, the tracks act as light scattering centers. The scattering of light off of these tracks causes a change of polarization that allows some of the light to be transmitted through the filters. The density ranges of track-etch neutron radiographs enhanced by the fluorescent dye method were found to be of the order of .37, while density ranges up to 2.4 were obtained with the Crossed Polaroid technique. Problems associated with these techniques and several suggested improvements are discussed.

INTRODUCTION

The track-etch method of neutron detection uses a neutron converter screen which is placed next to a layer of track recording material. The track recording material is an electrical insulator, usually glass, mica, or plastic. The converter screen material, which is chosen for its large neutron cross section and a prompt ion emission, is usually of uranium 235, lithium 6, or boron 10. The neutrons react with the nuclei of the converter screen material producing ionized particles which have a kenetic energy of the order of 5 MeV/amu. Ions formed close to the screen surface will leave the surface of the converter screen and penetrate the track recording material. Some of these ions that penetrate into the track recorder will cause damage along their paths as indicated in figure 1[1,2]. The requirement that must be fulfilled for a damaged track to be formed is that the linear rate of energy loss, dE/dx, must exceed some minimum value[3]. For a given ion dE/dx_{min} is a function of the track recording material. After the exposure to the neutron beam has been completed, the converter screen and track recorder are removed from the beam. The track recorder is then subjected to a chemical etch process. The etch solution preferentially attacks the damaged areas removing the insulator material and leaving in its place a pit or hole. Before the track recorder is etched, the damaged areas are only visible with an electron microscope. Etching enlarges the holes to the point where individual tracks can be seen with an optical microscope.

Track-etch was originally developed as a neutron dosimetry technique[4,5]. A suggestion was made by Furam, et. al, in 1966[6] that this technique could be adopted as an imaging system for neutron radiographs. In his disclosure for patent application in 1966, H. W. Alter[7] outlined the basic requirements for obtaining a track-etch neutron radiograph.

The track-etch imaging technique, as it is used for neutron radiography at Plum Brook Reactor, is shown in figure 2. The converter foil (.010 inch uranium 235 93% enriched) is placed behind the track recorder (a piece of Celenese 867-AA clear plastic film). The two materials are placed into a holder box (cassette) and held tightly together to form a film-foil sandwich. The box containing this sandwich is placed behind the subject in the collimated neutron beam. The neutron beam passes through the subject where, by absorption and scattering, its intensity becomes spatially modulated. This modulated neutron beam then passes through the film-foil sandwich where a portion of it reacts with the converter foil material to form energetic ions. Some of these ions will leave the converter foil and be recorded as tracks in the clear plastic track recording film. The exposure is continued until the recorded track density is in the order of millions of tracks per square inch. (A neutron exposure of about 2.5×10^{9} nvt is required[8] to produce a high quality track etch neutron radiograph by this method.) The film-foil sandwich is then removed from the neutron beam and separated. The plastic track recorder film is etched in an agitated solution of 3.25 normal potassium hydroxide at room temperature for 25 minutes. The uranium converter foil remains somewhat radioactive, but in general it can be reused immediately for as many as five additional exposures.

Track-etching produces a very fine neutron radiograph. The spatial resolution of a track-etch neutron radiograph, which is fixed by the range of the ions in the track recorder, is usually less than .0005 inch[9] (.0023 cm). The track-etch technique allows for indefinite integration of tracks to obtain the desired exposure. This makes this method attractive in cases where the neutron source is small. The technique is also insensitive to the gamma radiation content of the reactor neutron beam. The track-etch neutron radiograph, however, has one serious deficiency - very poor contrast. The usual optical density range of a track-etch is of order of 0.10. This is compared with a density of 2.5 for a normal Plum Brook Reactor indium transfer neutron radiograph.

This report describes two techniques which have been developed to increase the contrast of track-etch neutron radiographs. In the first technique described a fluorescent dye was deposited in the radiograph tracks. The radiograph was then viewed under ultra-violet light. Tracked areas were seen to fluoresce brightly while the untracked areas appeared black. The second technique described involved placing the track-etch radiograph between crossed light polarizing filters. In this technique the radiograph tracks were used as scattering centers to effect a change in polarization. This polarization change allowed light that had been scattered off of the tracks to penetrate the second (crossed) polaroid filter. Tracked areas appeared as bright white spots and the untracked area was a very dark blue.

EXPERIMENTAL EQUIPMENT

Plum Brook Reactor

The Plum Brook Reactor is operated by the National Aeronautics and Space Administration's Lewis Research Center, Plum Brook Station at Sandusky, Ohio. The reactor is a pressurized, light water-cooled and moderated, 60 megawatt test reactor. The reactor core shown in figure 3 is located approximately 20 feet (610 cm) below grade inside the steel pressure vessel, the Reactor Pressure Tank. The core is a 3x9 array of highly enriched uranium fuel elements. This active lattice is surrounded on all four sides by a beryllium reflector. The south side reflector is a 4x8 element beryllium array fitted with holes for experimental purposes.

The reactor pressure tank is surrounded by four 25-foot (761 cm) deep quadrants A, B, C, and D. All of the quadrants except quadrant B are filled with deionized water. The beam which is used for neutron radiography is extracted from the west face of the 4x8 array south side beryllium reflector section.

Neutron Radiograph Facility

The Plum Brook Reactor Neutron Radiograph Facility is shown conceptually in figure 4. The facility is located under 20 feet of water in reactor quadrant A. The major components of this facility are: (1) the ITA-1 (Instrument and Test Quadrant A No. 1 position) beam extraction tube, (2) the divergent neutron collimater, (3) the watertight sample holder shown in position at the rear of the collimator, and (4) the watertight foil cassette located inside of the sample holder.

The neutron beam is extracted from the core at the ITA-1 location by a 63 inch (160 cm) long 6.1 inch (15.5 cm) I.D. aluminum tube. The tube extends from quadrant A through the pressure tank to within ½ inch (1.27 cm) of the core reflector section's west side plate. The core end of the tube is closed by a flat aluminum plate which is welded across the tube end. The quadrant end of the tube is closed with an aluminum blind flange. During reactor operations, the tube is filled with helium at 10 psig. During reactor shutdown periods when quadrant A is drained, the tube is flooded with water to provide personnel radiation shielding protection.

The neutron collimator, shown in figure 5, is a 15 foot (457 cm) long divergent type collimator. The collimator is constructed entirely of 6061-T6 aluminum. The ¼ inch (.636 cm) thick entrance window is 1 inch (2.54 cm) square and the 3/8 inch (.952 cm) thick exit window has an area 3x30 inches (7.61 X76.1 cm). The collimation factor, L/D, is 180. The collimator is pressurized with 10 psig helium to prevent its distortion whenever the quadrant is filled with water. The entrance window of the collimator butts flush against the ITA-1 extraction tube exit blind flange. Bolted to the rear of the collimator is a receiver which accepts and positions the sample holder.

The watertight sample holder is a 5x5x45½ (12.7x12.7x115.5 cm) inch box constructed of aluminum. The holder has the capability of being loaded remotely under water (used for radioactive subjects), sealed, and the water replaced with dry helium. The foil cassette is positioned inside of the sample holder against the sample holder rear wall (away from the core).

The radiograph facility has an unfiltered neutron fluence of 4.0×10^7 nv at the start of a reactor cycle (usually about 15 days). This fluence increases over the power cycle to a maximum of 1.0×10^8 nv at the end of core life. The gold-cadmium ratio for the facility is 10.

Standard Penetrameter Subject

The standard penetrameter subject, shown in figure 6, is an assembly of three penetrameters. The three penetrameters used are: (1) a step wedge sensitivity penetrameter, (2) the Argonne National Laboratory Subject VISQI (Visual Qualitity Indicator*), and (3) a hexagonal hole resolution penetrameter. The sensitivity penetrameter is a six (6) step Plexiglas wedge. The thickness of the wedge steps ranges from .100 inch (.254 cm) down to .010 inch (.0254 cm). Each step has three holes drilled through it. These holes are 1T, 2T, and 3T in diameter where T is the thickness of the particular step in which the holes are drilled.

The second penetrameter of the assembly is the Subject Visual Quality Indicator developed by Dr. John Barton at the Argonne National Laboratory. The penetrameter is basically a three step plastic wedge. Each step has attached to it an identical group of absorbers. These absorber groups include cadmium and plastic wires of different diameters and a number of 1/16 inch (.159 cm) square blocks made of plastic, cadmium, indium, gadolinium, dysprosium, and lead. These blocks are made of varying thicknesses. Each step also has attached to it a .0197 inch (.05 cm) thick cadmium plate which has a series of holes drilled in it. This plate serves as a rough resolution penetrameter. The VISQI was designed to serve as a standard for comparisons of different radiographs from the same neutron radiograph facility. The choice of the materials used in the blocks is such that changes in the characteristics of the neutron beam or the exposure techniques from one radiograph to another will be detected by a change in the density of one or more of these blocks.

The third penetrameter used in this assembly is a resolution penetrameter. The penetrameter consists of eight hexagonal holes eloxed in a one inch square of a .001 inch (.0025 cm) thick gadolinium. The hole spacing ranges from .001 inch (.0025 cm) to .007 inch (.0178 cm) in .001 inch (.0025 cm) increments. The gadolinium is attached by tape to a 1½x3x.032 inch (3.8x7.6x.081 cm) aluminum plate to provide mechanical support.

CONTRAST ENHANCEMENT TECHNIQUES

Fluorescent Dye Method

The fluorescent dye technique used to enhance the contrast of track-etch neutron radiographs is illustrated in figure 7.

* The VISQI has been tentatively adopted as the standard penetrameter by the Association of Neutron Radiographers (ANR) at their first annual meeting at the 1970 Fall meeting of the ASNT.

In this technique a fluorescent dye, Zyglo*, is sprayed on to the tracked side of the track-etch neutron radiograph where it is allowed to stand for ten minutes. A cotton swab is then used to gently wipe the dye from the surface of the radiograph. The wiping operation is continued until all of the dye that can be seen with the naked eye is removed from the surface of the radiograph. Toward the end of the wiping operation the remaining dye appears as a grease haze on the radiograph surface. When this haze is eliminated the operation is terminated. In spite of the wiping some of the dye remains trapped in the tracks of the radiograph. (The cleaner normally used with the Zyglo process is not used as it tends to wash the dye out of the tracks.) The radiograph is then placed on a flat dull black surface in a darkened room. Ultra-violet is directed on to the radiograph at 45° from normal incidence. The dye that is trapped in the tracks absorbs the ultra-violet light and it begins to fluoresce. The tracked areas appear a bright yellow, while the untracked areas are essentially black. The fluorescing radiograph is then photographed from normal incidence. The ultra-violet light source is placed at 45° to the radiograph normal in order to reduce the background caused by the blue and violet components of the ultra-violet light source.

Crossed Polaroid Method

The technique of enhancing the contrast of track-etch neutron radiographs with crossed polaroid filters is schematically illustrated in figure 8. The track-etch negative is placed between two light polarizing filters which have their polarizing axis displaced by 90° from each other. The object of this method is to use the tracks in the radiograph as light scattering centers. Diffuse light is passed through the first filter (the polarizing filter), where it becomes polarized. The polarized light from this filter is passed through the track-etch radiograph and then through the second polaroid (the analyzing filter). The portion of the polarized beam that passes through a clear (untracked) area of the radiograph is transmitted with its polarization unchanged, and this portion of the beam is filtered out by the analyzing filter. The portion of the polarized beam that strikes a tracked area is scattered off of the tracks. The scattering process changes the polarization of that light so that a portion of it is now polarized parallel to the optical axis of the analyzing filter. This portion of the beam is then transmitted on to the viewer. The information recorded on a track-etch radiograph is the location of the tracks. Since only that light which is scattered off of the tracks is transmitted, it follows then that only track location information is transmitted to the viewer. In this way the crossed polaroid technique increases the contrast of the track-etch neutron radiograph. Since the direction

* Zyglo process is a trade name registered to Magnaflux Corporation, Chicago, Illinois.

of the tracks in a track-etch radiograph is random, a randomly directed (diffuse) light source is used to illuminate the polaroid-radiograph sandwich. This increases the probability of scattering during light transmission through the radiograph. The usual method of viewing the contrast enhanced radiograph is to place the polaroid-radiograph sandwich in a photographic enlarger and project the enhanced image on to a film.

EXPERIMENTAL RESULTS AND DISCUSSION

Fluorescent Dye

An unenhanced track-etch neutron radiograph, TE-55, of the standard penetrameter assembly is shown in figure 9. This radiograph (and all others in this section) was contact printed on Kodak AZO F4 paper. The poor contrast of the radiograph is plainly evident. A measure of the radiograph contrast is the density spread, Δ density, of the radiograph. In this case Δ density is defined as the optical density of the maximum tracked area, minus the optical density of an untracked area. The area of the resolution penetrameter was used as the untracked area and the area of one of the holes in the sensitivity wedge was used as the maximum tracked area. For a typical track-etch neutron radiograph like that of figure 9 the Δ density is of order of .05 to .10.

Figure 10 shows TE-55 after it has been contrast enhanced using the Fluorescent Dye technique. (The photograph has been enlarged to 1-1 for comparison with the unenhanced radiograph of figure 9.) It is apparent that the radiograph contrast has definitely been improved. This is confirmed by the measured Δ density which is now .37. Although the photograph is slightly out of focus, the .001 inch (.0025 cm) separation in the resolution penetrameter is clearly seen. Some of the absorber blocks on the third step of the VISQI are now visible. (These blocks were not visible in the unenhanced radiograph.) The 2T and 3T holes of the fourth step of the sensitivity wedge are now clearly seen whereas only the 3T hole of the third step is visible in the unenhanced radiograph. Deposition of the dye in the tracks is seen to be quite uniform, but some background interference is noted. This interference results from the ultra-violet light shining through the plastic and reflecting off of the backing material and into the camera. This effect results in the grainy background noted in the 3T hole area of the sensitivity step wedge and also in the area to the right of the resolution penetrameter.

Crossed Polaroid Method

A contrast enhancement of TE-55 by the crossed polaroid method is shown in figure 11. The Δ density of this figure is .71. The enhancement was obtained by placing the polaroid-radiograph sandwich in a photographic enlarger and projecting the image 1-1 onto a photographic film (Kodak SR-54). The enlarger was equipped with a fluorescent light which served as the diffuse light source. In this method the Δ density of the film is proportional to the exposure time in the enlarger. Figure 12 shows a plot of Δ density versus film exposure time. The curve indicates a maximum Δ density of 1.52 with an exposure time of 140 seconds. This is not, however, the maximum density range possible with the crossed polaroid enhancement technique. There are two reasons why Δ densities greater than 1.52 can be achieved; (1) light leaks in the polaroid filters prevent zero light transmission at the gadolinium resolution penetrameter. (The image of these light leaks tends to become larger with longer exposures thus having greater restrictive effect on the observed density), (2) the .001 inch (.0025 cm) thick gadolinium of the resolution penetrameter is not an opague neutron absorber (0.5 mean free paths in thickness). This further reduces the observed Δ density. In the radiograph shown in figure 15 a more efficient .040 inch (101 cm) thick cadmium resolution penetramemter (18 mean free paths in thickness) was used. When this radiograph was enlarged (2.4 times) so that the polaroid filter defects could be avoided with the densitometer, Δ densities ranging up to 2.4 were obtained for a 180-second exposure time. The 2.4 appears to be about the maximum Δ density obtainable with the polaroid filters that were used.

An inspection of figure 11 shows that all three holes of the fifth step and the 3T hole in the sixth step of the sensitivity step wedge are visible. The .001 inch separation of the resolution penetrameter is easily detected, and visibility of the VISQI absorber blocks and wires is dramatically improved over that of the unenhanced radiograph in figure 9.

Figure 13 is also a print of an enhancement of TE-55. This print was made using the crossed polaroid filters and the same enlarger settings that were used for figure 11. The only changes made were the substitution of a 6 inch (15.4 cm) diameter collimated incandescent light for the diffuse fluorescent light and the adjustment of exposure to account for the change in source intensity. These changes resulted in a marked decrease in the radiograph contrast. The contrast in this case was so poor that it appeared to be not much improved over that of the original unenhanced radiograph. Another important point can be seen by noting that the areas of light absorption in figure 13 are reversed from those of figure 11. In figure 11 light absorption is due to the crossed polaroid filters and transmission of light is dependent upon its scattering off of tracks in the radiograph. In figure 13, however, transmission is due to a slight birefringence of the plastic and absorption occurs because of the increased light path resulting from the diffusing surface in the tracked areas. As a check of this absorption reversal, a white paper towel, used as a diffuser screen, was inserted between the incandescent collimated light source and the radiograph crossed polaroid sandwich. When this was done, the absorption was again reversed to what it had been in figure 11 with the diffuse fluorescent light. This indicates that, for the crossed polaroid technique to work at all, a diffuse light source is required.

Figures 14 and 15 illustrate some of the problems associated with the crossed polaroid technique. The radiograph in figure 14, TE-70, was recorded on Dupont P-70 plastic film. This plastic has a nonuniform birefringence. When the track-etch radiograph was enhanced using the crossed polaroids, these birefringent areas rotated the polarized light so that some of it was passed by the analyzing filter causing the bright areas seen in the figure. The birefringence results from stresses set up in the plastic during its manufacture. This problem was solved by going to a plastic that is manufactured by a casting instead of extruding or pulling. Such a plastic, Celenese 867-AA, was used for the track-etch radiograph shown in figure 11. The result was that no birefringence was detected. The TE-70 enhanced radiograph also exhibits strong white light interference fringes. These fringes result from multiple reflections between the surfaces of the radiograph and of the polaroid filters. For the enhancement shown in figure 14 the radiograph was placed between the glass surfaces of the polaroids and the polaroid-radiograph sandwich was then held tightly together in the enlarger. This resulted in many intense fringes being formed. Some faint fringes in figure 11 can also be seen in the 3T hole of step 1 of the wedge penetrameter. For the enhancement shown in figure 11 two glass plates (microscope slides) were placed between the polaroid filters as spacers so that the surfaces of the radiograph were no longer held tightly against those of the polaroid filters. This resulted in the marked decrease in fringe intensity noted from figure 14 to figure 11. Because the radiograph was no longer held flat some areas of figure 11 are slightly out of focus. The fringe problem and the focus problem can be eliminated by using a holder for the filters and the radiograph that increases the air gaps between the filters and the radiograph while holding the radiograph flat.

The radiograph in figure 15, TE-9, was recorded on another type of plastic, General Electric's Lexan polycarbonate resin. This was the first material on which the crossed polaroid technique was evaluated. A different style of resolution penetrameter consisting of a series of drilled holes in a cadmium plate was used for this radiograph. The linear marks in the step wedge image are the result of mill role marks in the converter foil surface which prevented good contact between the track recorder and the converter foil during the exposure. This problem was eliminated by using precision rolled foils. Some non-uniform etching is to be seen at the left edge of the sensitivity step wedge. Due to the polarized light, stress points in the plastic are visible. These stress points appear as bright star-like points along the top edge of the resolution penetrameter. When viewed without the polaroids, none of these stress areas were detected. The rather large white area at the upper righthand corner of the radiograph was caused by a light leak during the enhancement. The Δ density of the TE-9 before enhancement was 0.15. After enhancement a Δ density of 1.22 was obtained for this radiograph.

Figure 16, a neutron radiograph, NRR 389, of the standard penetrameter subject taken by the conventional indium transfer method, is now presented for a comparison. (Indium transfer onto Kodak SR-54 film is currently the standard method employed for neutron radiography at Plum Brook Reactor. This method produces neutron radiographs of very high quality.) The Δ density of this radiograph is 1.95. If transmission through a clear unexposed portion of the film (not available on the track-etch radiographs due to space considerations in the cassette) is used in the Δ density calculation, instead of transmission through the neutron leaky resolution penetrameter, a Δ density of 2.73 is obtained. This second value excludes the effect of neutron leakage through the resolution penetrameter, and as such is a more accurate indication of the contrast obtained with this method.

The resolution of NRR 389 is seen to be at least .001 inch (.0025 cm). The visibility of absorber blocks and wires in the VISQI is superior to that of the radiographs enhanced by either the fluorescent dye or crossed polaroid method. Visibility is also superior in the sensitivity step wedge where all three holes of the sixth step are visible. A comparison between figures 11 and 16 shows that the quality of a crossed polaroid enhanced track-etch radiograph is not equal to that produced by the presently used indium transfer method. This enhancement technique, however, does produce a radiograph which must be considered of high quality and a substantial improvement of the unenhanced track-etch neutron radiograph.

CONCLUDING REMARKS

A comparison of the results of the two enhancement techniques, figures 10 and 11, with the unenhanced radiograph in figure 9 shows that a significant increase in contrast was obtained with each method. The Δ density measurements also confirm this visual observation with an increase from .10 to .37 for the Fluorescent Dye method and from .10 up to 2.4 for the Crossed Polaroid method.

The Fluorescent Dye method in its present embodiment is a cumbersome technique. Also since the phenomenon is photographed with a camera instead of being contact printed, quantitative measurements cannot be made from the enhanced radiograph. This technique can be simplified somewhat by contact printing on an ultra-violet insensitive film. This change should also increase the Δ density obtainable from this method by eliminating the U-V background that is presently a factor and provide for quantitative measurements from the enhanced radiograph. The Crossed Polaroid technique appears to be the much better of the two methods. Δ densities ranging up to 2.4 can be routinely expected. By using good optical grade polaroids one can expect a grain-free enhancement with densities comparable to those obtained with the more conventional methods of neutron radiograph imaging.

An interesting variation of the Fluorescent Dye method follows along the same method used in the Kodak LR-115[10] laminated plastic track recorder. In this variation a thin (about 8μ) layer of track sensitive plastic is laminated on to a thicker (about 100μ) layer of track insensitive clear polyester. The thick layer functions only as a mechanical support for the thin recording layer. The thin track recording layer is strongly loaded with a fluorescent dye. After the radiograph exposure has been completed, the radiograph is etched until the tracks perforate the thin layer. The etched radiograph can then be contact printed with ultra-violet light onto a U-V insensitive film or paper. The tracked areas, having had their dye removed by etching, will appear as black spots while the untracked areas will fluoresce brightly in the visible region.

The crossed polaroid method would also yield to the same type of laminated plastic variation. In this variation the thin track recording layer would contain one polaroid and the thicker support layer would contain the second polaroid filter. These filters would again be arranged in the crossed polaroid configuration. A track-etch radiograph recorded on this material would also be etched until the tracks perforated the thin layer. By etching, the track locations would be converted into imperfections in the polaroid filter. On viewing this radiograph with white light, the polarized light from the base material will be passed by these imperfections in the etched filter. The untracked areas on the other hand will remain dark because of the absorption of the crossed polaroids. This method should be quite effective because of the blocking efficiency of crossed polaroids is usually of the order of 95 percent or better. The resulting radiograph can then be either projected or contact printed.

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TRACK FORMATION SEQUENCE IN INSULATOR SOLID

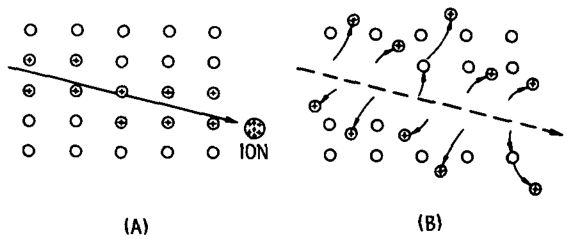

Fig. 1

NEUTRON RADIOGRAPHY BY TRACK-ETCH METHOD

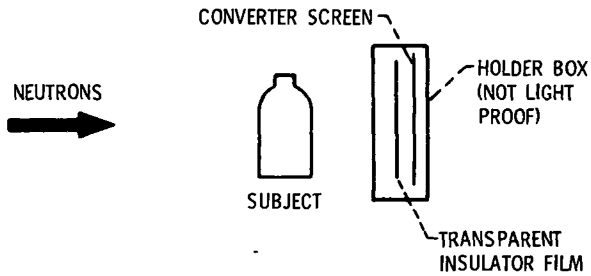

Fig. 2

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CUTAWAY PERSPECTIVE DRAWING OF REACTOR TANK ASSEMBLY

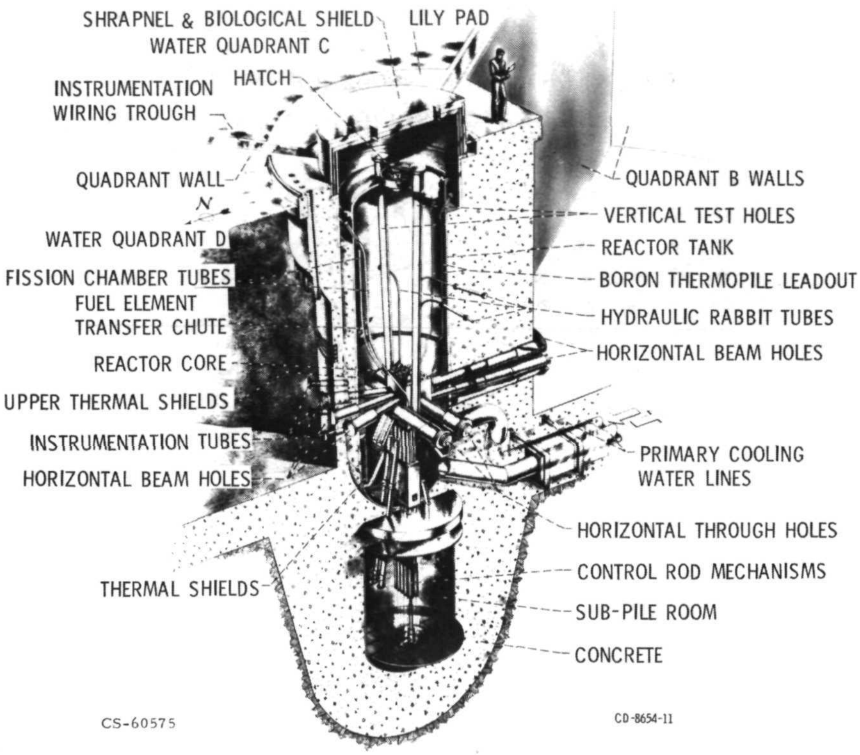

Fig. 3

NEUTRON RADIOGRAPH FACILITY

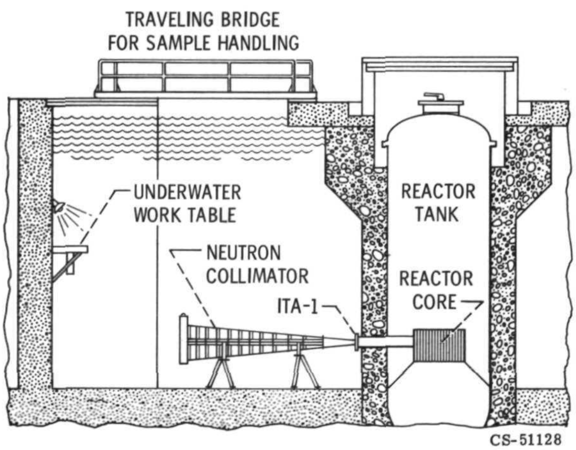

Fig. 4

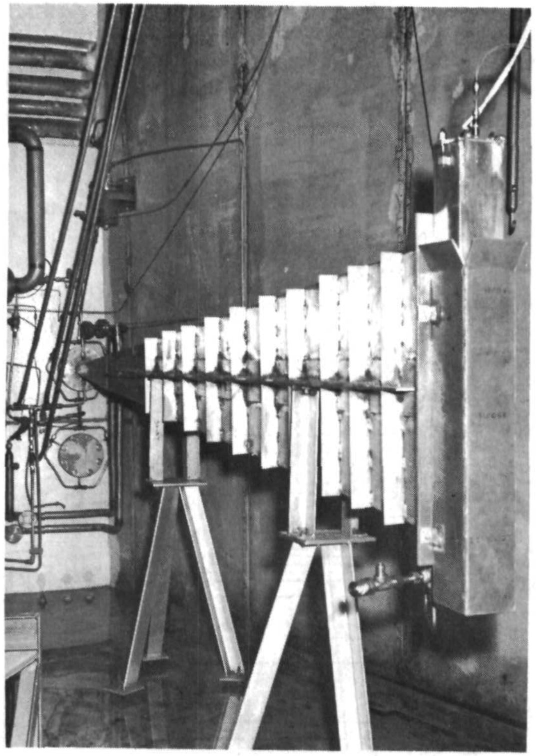

Fig. 5. - The divergent neutron collimator.

STANDARD PENETRAMETER SUBJECT

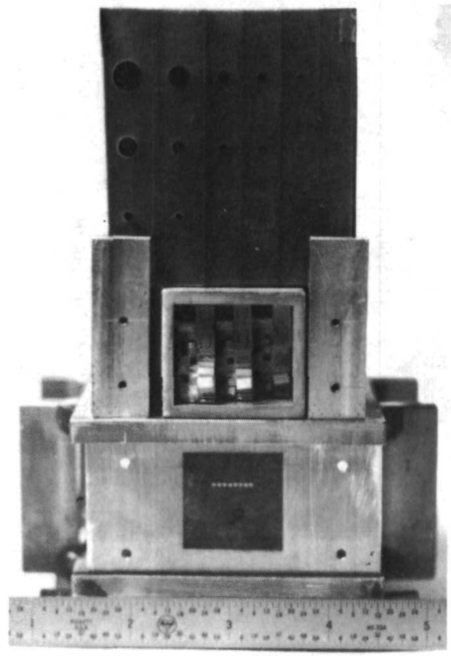

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Fig. 6

FLUORESCENT DYE METHOD

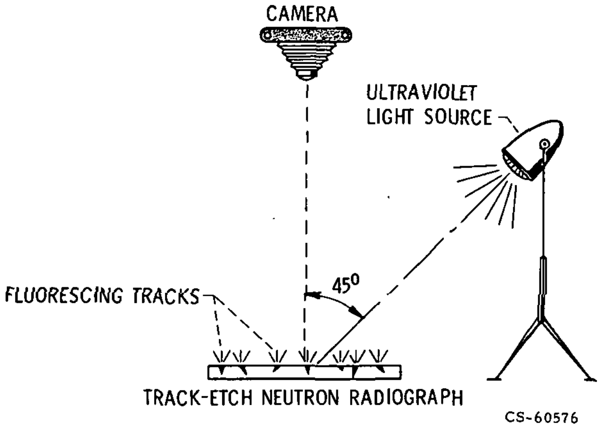


Fig. 7

ILLUSTRATION OF CROSSED POLAROID METHOD

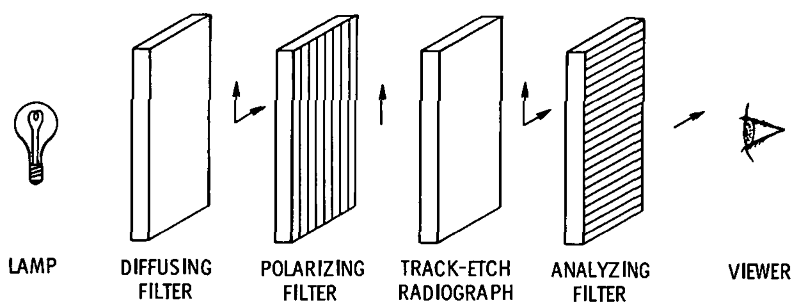
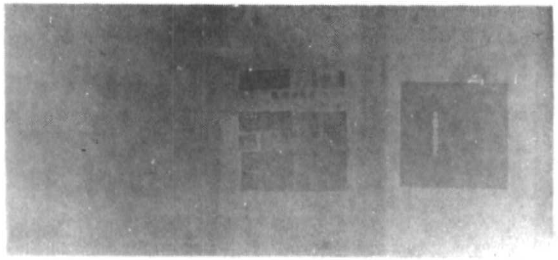


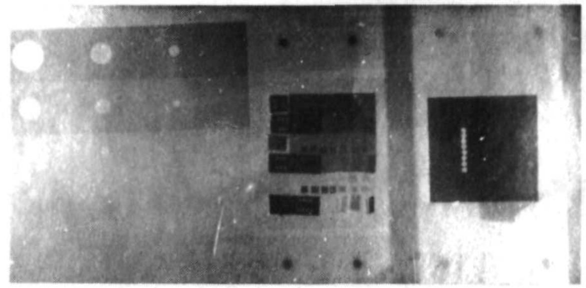
Fig. 8

CS-60571



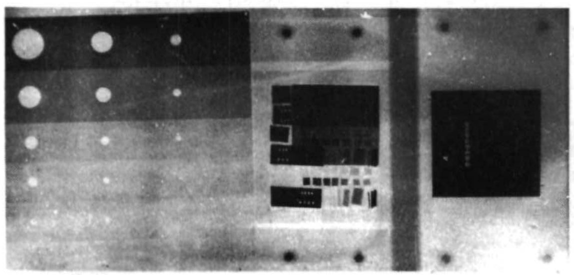
CS-60569

Fig. 9. - Track-etch radiograph, TE-55, shown here before contrast enhancing.



CS-60568

Fig. 10. - Track-etch neutron radiograph TE-55 after enhancement by the fluorescent dye technique.

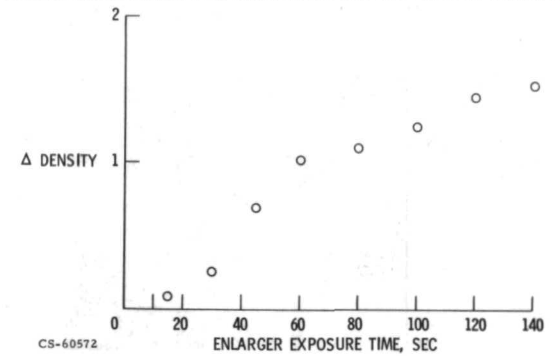


CS-60567

Fig. 11. - Track-etch neutron radiograph TE-55 after it has been contrast enhanced using the crossed polaroid technique.

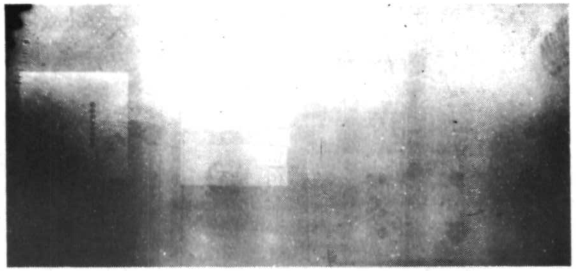
PLOT OF Δ DENSITY VERSUS EXPOSURE TIME

FROM THE ENLARGER FOR TE-55 ENHANCED BY CROSSED POLAROID TECHNIQUE



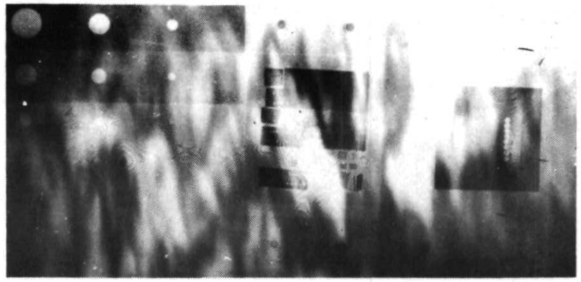
CS-60572

Fig. 12



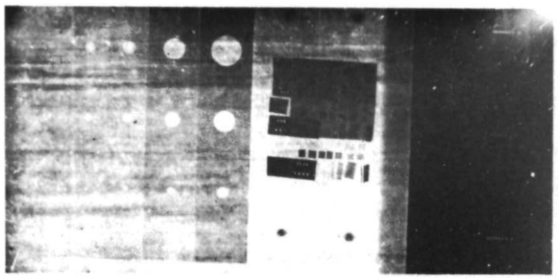
CS-60570

Fig. 13. - Track-etch neutron radiograph TE-55 contrast enhanced using the crossed polaroid technique but with a collimated instead of a diffuse light source.



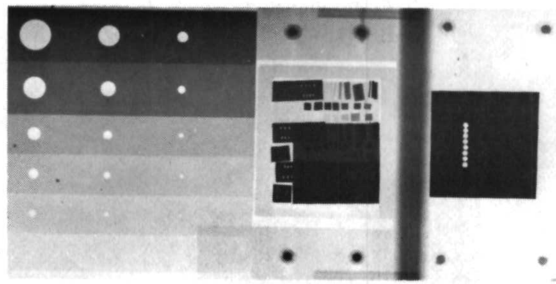
CS-60566

Fig. 14. - Track-etch neutron radiograph TE-70, recorded on Dupont P-70 plastic film and contrast enhanced by the crossed polaroid technique.



CS-60565

Fig. 15. - Track-etch neutron radiograph TE-9 recorded on Lexan polycarbonate resin plastic and contrast enhanced by the crossed polaroid technique.



CS-60564

Fig. 16. - Neutron radiograph NRR 389 recorded by the indium transfer method on Kodak SR-54 film.

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