NEUTRON RADIOGRAPHY REPORTS WORLWIDE
1964-1977

CONTENTS

This indexed compilation, edited by John P Barton, is based on the Neutron Radiography Newsletter 1964-1977. It was first issued in 1977 preceding the First World Conference on Neutron Radiography held 1981.

PREFACE

Only 45 years ago the neutron was unknown. About 20 years ago a useful quality neutron radiograph was unknown. When the neutron radiography newsletter was started thirteen years ago, by Mr. Harold Berger, there were probably only half a dozen individuals actively working in the field.

Since then, interest has spread to the extent that letters are now received frequently, from all parts of the world, from individuals who explain they are starting work in neutron radiography and would like to obtain back copies of the newsletter. Supplies of such back editions have long been exhausted: hence, this edited combined volume.

It is hoped this combined volume will provide helpful information on who has done what, and where. If this leads in the future to some more useful correspondence between neutron radiographers, some fruitful phone calls, some friendly visits; then it has served its main purpose. The volume may also provide a record, written by the participants themselves, of how one technical field has developed from its early roots.

Thanks are due to the individual neutron radiographers who have provided the material of which the newsletter is composed. Thanks are also due to the American Society for Nondestructive Testing which has agreed to provide a base for distribution of the newsletter, while allowing its international and interdisciplinary nature to be preserved.

John P. Barton
Corvallis, Oregon

December 1977

PART I

RECORD OF ACTIVITIES
(WHO HAS DONE WHAT, AND WHERE)

NUMBER 2. 1965

ARGONNE NATIONAL LABORATORY
Argonne, Illinois
H. Berger

A thermal neutron image intensifier, developed in cooperation with the Rauland Corporation, Chicago, has recently been placed in operation at Argonne's Juggernaut reactor. The intensifier appears capable of presenting an immediate visible image of incoming thermal neutron intensities as low as 10^3 n/cm^2-sec. Used with a thermal neutron beam intensity of 2.6×10^7 n/cm^2-sec, the intensifier tube provides an output phosphor brightness of about 20 ft.-Lamberts. This light intensity is easily detected by a closed circuit vidicon television system. The neutron television system has shown a resolution of about 0.5 mm, has followed high contrast object movements as fast as 5 m/min without blurr, has demonstrated thickness changes in a limited thickness range of steel and uranium as small as 4%, and has sufficiently low response to high gamma radiation that it can be used to inspect reasonably radioactive materials. Further improvements in relative neutron-gamma response, and in resolution capability are under study.

ARGONNE NATIONAL LABORATORY
Idaho Falls, Idaho
D. C. Cutforth

This organization is interested in non-reactor neutron source inspection systems.

BATTELLE MEMORIAL INSTITUTE
Columbus, Ohio
D. A. Dingee

Battelle has been using neutron radiography for inspection of radioactive reactor fuels.

GENERAL ELECTRIC COMPANY
Vallecitos Atomic Laboratory
Pleasanton, California
J. M. Gerhart

We are presently engaged in a development program which has as its objective the fabrication of α,n sources utilizing Ac-227 and Th-228 as the radioisotopes. It would seem that these neutron sources would be especially useful in neutron radiography work due to the high neutron output per unit volume. We presently anticipate that the neutron output will be approximately 8×10^7 n/sec-cm^3 for a Th-228 source and 7×10^6 n/sec-cm^3 for an Ac-227 source. The half lives of Th-228 and Ac-227 are 1.9 and 22 years, respectively.

A report describing these source studies, entitled, The Use of Ac-227 and Th-228 In Radioisotope Heat and Neutron Sources," by J. M. Gerhart and C. P. Ruiz (presented at the American Nuclear Society Annual Meeting, June, 1964), is available from General Electric.

LOS ALAMOS SCIENTIFIC LABORATORY
Los Alamos, New Mexico
B. L. Blanks

Experiments are in progress as a part of the current research and development program in neutron radiography in Group GMX-1 at the Los Alamos Scientific Laboratory. These experiments are designed to yield information on several aspects of the neutron radiographic process and its application to the solution of practical problems. Investigations of the response of gadolinium film-foil combinations to thermal neutrons and thermal neutron collimation studies are presently in progress. In addition, studies are being made to determine the feasibility of utilizing neutron radiography for the detection of voids in thin sections of high explosives.

RAULAND CORPORATION
Chicago, Illinois
W. F. Niklas

Neutron image intensifier tubes have been developed and tested in a cooperative program with Argonne National Laboratory.

ST. JOHN X-RAY LABORATORY
Califon, New Jersey
H. R. Isenburger

Limited experimental work has been performed using an actinium-beryllium neutron source.

THIOKOL CHEMICAL CORPORATION
Wasatch Division
Brigham City, Utah
D. W. Rathman

This work has involved the potential of the Radiographic Linac as a neutron source, or controllable mixed radiation source, for the purposes of investigating neutron radiography and the effects of radiation on materials.

TOKYO SHIBAURA ELECTRIC CO., LTD.
Central Research Laboratory
Kawasaki, Japan
K. Ogawa

A 4 x 10^{10} n/sec yield Cockroft-Walton (200 Kv) accelerator was briefly studied as a source of thermal neutrons (the 14 MeV neutrons were moderated in a 70 x 70 x 70 cm paraffin cube) with limited success. A strong gamma ray background did present problems.

UNIVERSITY OF BIRMINGHAM
Department of Physics
Birmingham, England
J. P. Barton

In studies of thermal neutron radiography the penetration and contrast sensitivity achievable has received most attention. The importance in this respect of the role of scattered neutrons has been discussed in a paper to be published (Applied Materials Research), and measurements presented in that report indicate how the scattered neutron effect may be predicted and appropriate precautions taken.

The optimization of small portable sources for neutron radiography has been considered. A series of measurements were carried out giving the beam strength and collimation obtainable from a polonium-beryllium source with a variety of collimators and moderator geometry. The results are not considered worthwhile reporting in detail at this stage.

Consideration is being given to some scintillator methods for neutron photography, and some attention is also being given to the problems of gamma ray interference and fine detail sensitivity in the thermal neutron technique.

The advantages envisaged for resonance energy neutron techniques include (1) greater penetration for certain materials, (2) high contrast for very small quantities of certain materials, (3) exceptional image sharpness, (4) the possibility of discrimination against scattered neutrons by virtue of their energy loss, particularly for objects which contain hydrogen. The technique may also allow elements to be alternately transparent and opaque at different neutron energies, and may permit a degree of identification. A report on this is being submitted for publication.

A special crystal monochromator has been designed, constructed, and tested for this purpose. Single crystals of aluminum measuring 6" x 2" diameter have proved satisfactory. Radiographs have been obtained for indium resonance neutrons with exposure times of the order of a few minutes. The facility has now been modified to enable studies over a range of epithermal energies.

Concerning fast neutrons the advantages envisaged include the high penetration of very dense materials such as lead and the utilization of portable and relatively inexpensive sources. The applications seem to be limited. A little work has been performed using a 200 KV deuteron on tritium source, but without any success worth reporting. Preliminary attempts to use uranium as a detector by virtue of its fission cross section proved abortive, presumably because the source strength did not overcome the natural activity of the uranium. Some future experiments using a 20μ Amp deuteron beam at up to 20 MeV from a cyclotron are possible.

The possibilities of using neutron radiography for biological research or perhaps medical diagnosis have been considered. It was concluded that some important advantages might exist, particularly if the scattering effect of hydrogen could be reduced by the resonance energy technique. A report on this was published (Phys. Med. Biol., 9, No. 1, 1964). Following this, studies of the resonance energy technique have confirmed some of these predictions (Phys. Med. Biol., 10, No. 2, 1965). The question of the extent of tissue damage from thin neutron beams has also been considered in more detail. Experimental measurements using a network of small photographic dose detectors suspended in a volume of tissue equivalent liquid were not very successful. Theoretical consideration of the problem showed more promise particularly using Monte Carlo methods.

The contributions of some post-graduate research students to these studies are gratefully acknowledged, as is the assistance of staff of the U.K.A.E.A.

UNIVERSITY OF NEVADA
Nuclear Engineering Department
Reno, Nevada
D. F. Dickinson

An Atomics International model L-77 reactor (licensed power of 10 watts) is available. Also available is a Texas Nuclear Neutron Generator, model 9505, which has a fast neutron yield of 10^{11} n/sec. There is interest in using these equipments for neutron radiographic biological studies.

UNIVERSITY OF WASHINGTON
Chemical Engineering Department
Seattle, Washington
J. Ferris

Equipment for neutron radiography investigations is being collected; the immediate interest is the possible detection of hydrogen in titanium metal.

****

NUMBER 3. 1965

ARGONNE NATIONAL LABORATORY
Argonne, Illinois
H. Berger

A second thermal neutron image intensifier tube has been placed in operation and an evaluation is now in progress. The light yield from the second tube is about 30 percent greater than that from the first one. A resolution improvement has also been observed, because of a closer spacing between the tube window and the detecting scintillator target. Future plans include a more complete evaluation of this tube and future tubes, plus some application studies in which the immediate response of the imaging system can be used to advantage.

ARGONNE NATIONAL LABORATORY
Idaho Falls, Idaho
D. C. Cutforth

A computer program to optimize the design of a Sb-Be radioactive neutron source is now in operation. Plans now call for experimental confirmation of the theoretical results obtained. In addition, a transient reactor neutron source (TREAT) is now being considered, for neutron radiographic application use.

BROOKHAVEN NATIONAL LABORATORY
Upton, L. I., New York
H. L. Atkins

Biological studies are continuing. Latest efforts have been directed at improving collimation of the imaging neutron beam.

INSTITUTE OF NUCLEAR RESEARCH
Warsaw, Poland
M. Radwan

Application studies are now in progress using the nuclear reactor "EWA" as a neutron source.

LOS ALAMOS SCIENTIFIC LABORATORY
Los Alamos, New Mexico
B. L. Blanks, D. A. Garrett and R. A. Morris

Neutron radiographic and neutron gaging application studies are in progress, along with more basic studies of neutron detection and neutron collimation methods.

NOTTINGHAM UNIVERSITY
Department of Mechanical Engineering
Nottingham, England
J. H. Hamilton

Plans are under way to study the use of an accelerator neutron source (5×10^{10} n/sec) as a means of obtaining a thermal neutron beam.

RAULAND CORPORATION
Chicago, Illinois
W. F. Niklas

Thermal neutron image intensifier tube development is continuing. Such tubes are now being offered commercially.

SANDIA CORPORATION
Albuquerque, New Mexico
D. W. Ballard, N. Knudsen

A source facility for neutron radiographic application studies is now in operation at Sandia's SERF reactor. A beam intensity in excess of 10^7 n/cm^2-sec is available. A soller slit collimator has yielded excellent resolution results.

TOKYO METROPOLITAN ISOTOPE CENTER
Tokyo, Japan
M. Kobayashi

A Triga-II reactor has been used to study neutron beam collimation and some application possibilities. A nylon wire penetrameter has proved to be a very useful test object.

TOKYO SHIBAURA ELECTRIC CO., LTD.
Central Research Laboratory
Kawasaki, Japan
K. Ogawa

A small (100 KW) reactor, the TTR-1, is being used as a neutron source for neutron radiographic studies. The beam facility is being used to demonstrate the practicality of neutron radiography for industrial applications. In addition, the influence of various collimators on image quality is being studied. Image quality is being studied by means of a spectrum analysis of the line spread function (a report on this work is being prepared for publication).

UNIVERSITY OF BIRMINGHAM
Physics Department
Birmingham, England
M. R. Hawkesworth and L. Holland

Much of the work initiated by John Barton is being continued. Present emphasis is being placed on a thorough evaluation of neutron scintillators for imaging applications and continued studies of the influence of the use of cold and epithermal energy neutrons for radiography.

UNIVERSITY OF GRENOBLE
Grenoble France
J. P. Barton

Experimental work with neutron accelerators as sources for neutron radiography is planned.

UNIVERSITY OF MISSOURI
School of Mines and Metallurgy
Rolla, Missouri
D. S. Eppelsheimer and M. Arment

Neutron radiograhic examination of a cadmium-tin alloy as a complementary tool to optical metallography has been investigated as a means of studying internal structure. Future research will be directed toward refining of the exposure techniques, specimen preparation and the extension of the method to other suitable alloy systems.

****

NUMBER 4. 1966

NEUTRON RADIOGRAPHY DEVELOPMENT PROGRAMS

ARGONNE NATIONAL LABORATORY
Argonne, Illinois
H. Berger

Neutron image intensifier tubes are under investigation in a cooperative program with The Rauland Corporation. The latest intensifier tube has a 15 cm diameter useful input area instead of the 22 cm tubes previously evaluated. The new tube appears to be much superior to the previous tubes in terms of light yield, and in terms of relative neutron-gamma response. Application studies are in progress.

ARGONNE NATIONAL LABORATORY
Idaho Falls, Idaho
D. C. Cutforth

A computer program to optimize the design of a Sb-Be radioactive neutron source has yielded some preliminary information. The work is continuing.

BATTELLE MEMORIAL INSTITUTE
Columbus, Ohio
W. A. Carbiener

Neutron radiographic examination of irradiated fuel specimens is being carried out, utilizing the indium transfer method. The process utilizes a 2 MW reactor as a neutron source and the reactor pool water as a biological shield. Approximately 75 specimens have been examined ranging in length from 3 to 50 inches and diameters from 0.3 to 0.6 inches. Studies are currently underway to improve the underwater technique and examine specimens up to 10 feet in length.

BUNDESANSTALT FUR MATERIALPRUFUNG
Berlin, Germany
Dr. R. Neider, H. Schnitger

An accelerator neutron source is available and plans are underway to use the source for neutron radiographic work.

CENTRE D'ETUDES NUCLEAIRES
Cadarache, France
G. Lachese

Preparations to use neutron radiography to inspect radioactive objects are being made. A neutron beam facility for this work is being prepared at the reactor at Cadarache. A review report on some published material on neutron radiography has been prepared within the Department de Metallurgie.

CENTRE D'ETUDES NUCLEAIRES
Grenoble, France
J. P. Barton

This investigation involves the possibility of using accelerator sources for neutron radiography. A range of accelerators of different sizes are being used and the object is to see to what extent very small inexpensive sources now available from a number of suppliers can be useful for this application. Some encouraging results have been obtained. Geometries tried include source targets suspended in air with all walls several feet away, and sources surrounded by large volumes of material leaving a narrow channel for the emergent beam. With appropriate arragements, direct exposure thermal neutron radiography can be performed without serious interference from X-rays, gamma rays or fast neutrons. Radiographs can be obtained using an inexpensive 120 KV source of 5 x 10 n/sec output in exposure time of only a few minutes. This work is being done in the Department des Radioelements.

J. P. Peurves

Within the Section des Piles, work is being done to prepare a collimator for neutron radiography to be inserted into the water surrounding the 15 MW swimming pool reactor SILOE. The object is to examine highly radioactive objects under the shielding water without extracting them from the reactor pool.

CENTRE D'ETUDES NUCLEAIRES

Saclay France
J. L. Boutaine

Work has begun on the problem of using radioactive sources for neutron radiography. This study, based in the Section d'Application des Radioelements, is in parallel to the study of small accelerator sources at Grenoble. Initial experiments on moderator and collimator arrangements are underway using a 1 curie Po-Be source and the use of a 50 curie Po-Be source is planned. Application areas of particular interest involve the inspections of brazed joints and of plastic materials. An internal report on the availability of metal foils suitable for neutron radiography work has been prepared.

RAULAND CORPORATION

Chicago, Illinois
W. F. Niklas

The development of thermal neutron image intensifier tubes is continuing. The latest tube, evaluated at Argonne National Laboratory, incorporated several changes which have resulted in increased light yield and in improved relative neutron-gamma response.

SANDIA CORPORATION

Albuquerque, New Mexico
N. Knudsen

Application studies are underway. The neutron radiographic source used is Sandia's SERF reactor; a beam intensity of 10^7 n/cm^2-sec is available.

TOKYO METROPOLITAN ISOTOPE CENTER

Tokyo, Japan
M. Kobayashi and S. Maeda

The comparative diffuseness of radiographic images prepared by gamma rays and by neutrons has been studied. A report on this work is planned for presentation at the Joint Meeting on Application of Radioisotopes to Science and Engineering, to be held in Japan in Spring, 1966.

TOKYO SHIBAURA ELECTRIC CO., LTD.

Central Research Laboratory
Kawasaki, Japan
K. Ogawa

Spectral analysis studies are continuing, as reported in Newsletter No. 3. Application studies have received special attention, and inspected materials have included canned UO_2 fuel pellets, control rods, and complex structures involving several materials. In this latter category, useful neutron inspections of boron films on aluminum (for use in neutron chambers) have been made. Similar inspections of boron films on stainless steel were less successful. Most application work has been done with the direct exposure method with gadolinium foils. Satisfactory results have been obtained.

UNIVERSITY OF BIRMINGHAM

Department of Physics
Birmingham, England
M. R. Hawkesworth

The present program includes a study of all promising converter screen-film combinations for neutron image detection. Particular emphasis has been placed on the use of Nuclear Enterprises' NE421 screens and lithium loaded glass scintillators and Ilford films Industrial A and HP3, Kodak Royal Blue, and other fluorographic films. Reciprocity failure and characteristic curve data are being collected. Gadolinium foil techniques with Ilford G film are also being used extensively as a standard for comparison with the other film combinations, because of the reciprocity response and because of the sharp images. The reciprocity failure studies are far enough along so that efforts to use these detectors with non-reactor neutron beams are beginning.

UNIVERSITY OF PARIS
Laboratoire de Chimie Physique
M. Maurette

Several neutron radiographic application studies are presently under consideration.

UNIVERSITY OF NOTTINGHAM
Department of Mechanical Engineering
Nottingham, England
J. H. Hamilton

The program involves a study of the possibilities of a 5×10^{10} n/sec accelerator source with the target situated at the center of a large water tank. Object and photographic detector are positioned at the end of a movable aluminum collimator. A scintillator system provided by Nuclear Enterprise, Ltd. provides best contrast while indium foil converter methods provide best picture sharpness. Preliminary results reveal, for example, 1/8 inch of rubber behind 2 inches of lead.

****

NUMBER 5. 1966

ARGONNE NATIONAL LABORATORY
Argonne, Illinois
H. Berger

The cooperative program with The Rauland Corporation for the development of a neutron image intensifier tube has continued. More detailed performance characteristics of the newest, 15 cm target tube are available. High contrast resolution capability is 0.35 mm. Light yield is linear with thermal neutron intensity at least over the range 10^4 to 2×10^7 n/cm^2-sec; at the high neutron intensity, the output phosphor brightness is approximately 100 ft-Lamberts. Also at the high value of neutron intensity, a cobalt-60 gamma radiation intensity as high as 10,000 R/hr at the tube face, causes relatively little degradation in the observed neutron image. Speed of response is such that high contrast object movement as fast as 5 m/min can be observed with little image blurr, using a vidicon closed-circuit TV system. With a faster TV camera tube, such as an image orthicon, object motion as fast as 15 m/min has been followed. The more sensitive image orthicon system has also permitted us to observe televised gross neutron images (at 1/30 sec frame rates) for incoming thermal neutron intensities as low as 1000 n/cm^2-sec. Gross brightening of the output phosphor could be observed via TV for intensities as low as 200 n/cm^2-sec. The measured light gain of the neutron image intensifier tube, as compared to a Nuclear Enterprises NE421 neutron scintillator is about 2×10^4.

I. R. Kraska

Neutron radiography of lead in thicknesses as great as 12 inches has yielded good results. Penetrameter sensitivities of 5% or better can be achieved over the range 1 to 12 inches. These results are inconsistent with previously reported neutron scatter factors for lead. This aspect of the work is being further studied.

ARGONNE NATIONAL LABORATORY
Idaho Falls, Idaho
D. C. Cutforth

Experimental confirmation of some of the neutron source computer program results has been obtained with studies with a Sb-Be neutron source. The source activity has not been accurately measured but is between 500 and 1000 curies. This source yielded a 2 x 2 inch collimated thermal neutron beam intensity (20 inch long collimator) of about 5 x 10^4 n/cm^2-sec. Radiographic results with a dysprosium screen transfer technique and medium speed X-ray film look very promising. Further improvements in neutron intensity and/or collimation appear to be possible.

ATOMINSTITUT DER OSTERREICHISTCHEN HOCHSCHULEN

Vienna, Austria
H. Rausch and G. Saringer

Our investigation concerns the detectability of thickness variations of plastics enclosed between thick steel plates and the possibility of identifying hydrogen inclusions in steel. The measurements were done by means of the direct exposure method using Gd-foils. The neutrons were taken from the TRIGA-Mark II reactor and were collimated by means of two Soller-collimators (horizontal and vertical). For improving the uniformity of the neutron beam, we are constructing a collimator to simulate a point source. This is of special interest for further investigations concerning hydrogen gas inclusions in steel. Investigations dealing with the detection of the poisoning of reactor fuel elements by means of the dysprosium transfer method are planned. Another experiment concerns the determination of the mass spectrum of the different Gd-isotopes taken from a mass separator.

CENTRE D'ETUDES NUCLEAIRES

France
J. P. Barton, P. Corompt, and J. Perves at Grenoble; G. Lachese and M. Desandre at Cadarache and J. L. Boutaine at Saclay

Studies of the possibility of using accelerator and radioactive sources are continuing and a report will be prepared as soon as possible. Under water neutron radiography has been carried out on the research reactors MELUSINE (4 MW) and SILOE (15 MW) at Grenoble and has proved very useful. A report is in preparation for publication. More sophisticated apparatus for performing this under water radiography is now being designed. The low power reactor PEGGY has been one of several neutron sources used for neutron radiography development at Cadarache. Applications under consideration here are the possible construction of a neutron radiography facility for the 30 MW research reactor PEGAS, and the separate problem of the examination of irradiated fuel elements from the national nuclear power program reactors. At Saclay the small reactor ISIS is being equipped for neutron radiography. This may be used in conjunction with the 50 MW reactor OSIRIS.

GENERAL DYNAMIC CORPORATION

Ft. Worth, Texas
W. E. Dungan

A reactor facility for neutron radiographic studies is now in preparation. Initial plans involve the use of this facility for experimental evaluation of neutron techniques for the inspection of small explosive devices.

GENERAL ELECTRIC COMPANY

Vallecitos, Pleasanton, California
C.E. Porter

A 30 KW graphite reactor is being used for a variety of neutron inspection applications. Beam intensity available is about 10^6 n/cm^2-sec. Both direct exposure and transfer exposure methods can be used. Another neutron image detection method utilizing etching of radiation damaged areas in glass or plastic films is also being studied. This technique is reasonably fast, is insensitive to gamma radiation and provides excellent resolution. One can integrate image information for an infinite time and with patience one can obtain digital dosimetry information (one track in the detector is obtained for about 10 incident neutrons). Additional information on this method can be found in, "Track Etching - Some Novel Applications and Uses;" S.C. Furman et al., Trans. ANS, 9, 598 (Oct., 1966).

PRINCETON UNIVERSITY

Department of Aerospace and Mechanical Sciences, Princeton, New Jersey
J. Grey and R. Moss

The use of a thermal neutron image intensifier tube shows great promise as a diagnostic tool for examination of phase changes within a heat pipe. The heat pipe is a device for transferring heat at essentially isothermal conditions and has numerous applications in the general field of space nuclear power supplies. Specifically the image intensifier tube will be used to study the boiling process within the wick structure of the heat pipe; these observations would be impossible using any other radiographic technique. Construction of a neutron radiography facility for this study is now underway and will utilize the Industrial Reactor Laboratories 5.5 megawatt reactor as a neutron source.

TOKYO METROPOLITAN ISOTOPE CENTER

Tokyo, Japan
M. Kobayashi and S. Maeda

Neutron image quality is being studied. In particular, the influences of unparallelism of the neutron beam and of the process of image transfer are under investigation.

TOKYO SHIBAURA ELECTRIC CO., LTD.

Central Research Laboratory
Kawasaki, Japan
K. Ogawa

Recent work has led to the successful development of a neutron television system utilizing a multi-stage image intensifier. The gain of the intensifier is 5 x 10^4. Studies with this system are presently in progress with a second beam facility at the TTR-1 reactor.

UNIVERSITY OF BIRMINGHAM

Department of Physics
Birmingham, England
M. R. Hawkesworth and L. Holland

Emphasis of the present effort is tending toward studies of converter-film detection characteristics, and the optimization of small neutron source moderator systems using theoretical methods.

AIR FORCE MATERIALS LABORATORY

Wright-Patterson Air Force Base, Ohio
A. Bauer

A beam port at the Air Force Nuclear Engineering Test Facility is being readied for neutron radiographic use. The reactor is a 10 MW, heterogeneous, highly enriched uranium fueled, tank-type reactor, cooled and moderated by light water. A collimated thermal neutron beam intensity in the order of 10^7 n/cm^2-sec is anticipated from the 5 inch diameter collimated beam. The facility will be available to the Air Force laboratories at Wright-Patterson and to their contractors.

****

NUMBER 6. 1967

ARGONNE NATIONAL LABORATORY

Argonne, Illinois
H. Berger and I. R. Kraska

Some development and application work with the neutron image intensifier system continues. Also under way are studies of two relatively new neutron image detection methods. Thermoluminescent detectors have been investigated for neutron radiography in collaboration with J. Kastner. Total thermal neutron exposures now required for this technique are about 10^9 n/cm^2. Object thickness changes as small as 10% have been observed; a high contrast resolution as small as 0.125 mm has been obtained. The track-etch technique with enriched uranium foils and cellulose nitrate films has yielded about the same contrast, but about an order of magnitude better resolution. The total exposure required is about 2 x 10^9 n/cm^2. The latter technique is completely gamma insensitive and is, therefore, attractive as a detection method for poor n-γ ratio neutron beams and for the inspection of radioactive material. Neutron inspection of thick metal samples is also under investigation; the study includes scatter factor determination and its influence on image quality.

ATOMINSTITUT DER OSTERREICHISCHEN HOCHSCHULEN
Vienna, Austria
H. Rauch, *et al*.

A cone shaped collimator has been designed which gives the same angular divergence and the same intensity as a two directional Soller collimator (horizontal and vertical slits) and a much higher homogeneity of the neutron beam. The collimator has been built within a beam hole of the TRIGA reactor. Its length is 218 cm, the neutron entrance diameter (near the reactor reflector) is 1.5 cm, and the outlet exposure position diameter is 12 cm. The entrance diameter is defined by means of B_4C and lead layers, and the collimator walls are coated with $B(OH)_3$ to avoid wall scattering. The previously used Soller collimator system has been described in a publication by H. Rauch and G. Saringer,(1) and the new collimator is described in an unpublished internal report by H. Rauch and K. Chountas.(2) Inhomogeneities of plastics enclosed between thick steel plates have been detected with greater sensitivity with the new cone-shaped collimator.

Work in progress by H. Rauch and K. Chountas:

Investigations of the mass density distributions of the various Gd-isotopes taken from a mass separator, and the determination of the absolute mass density when the mass separation conditions are changed. Investigation of irradiated TRIGA fuel elements by means of the dysprosium transfer method.

Work in progress by H. Rauch and W. Kraus:

Determination of the mean number of conversion electrons per neutron absorption in Gd-157.

CENTRE D'ETUDE NUCLEAIRES
Cadarache, France
G. Lachese

An accelerator source of neutrons is now being considered for hot cell neutron radiographic examination of spent fuel elements from the national electricity generating power reactors.

C. Desandre

Several neutron sources have been used since October and different experiments undertaken. For the reactor Pegase (35 MW) the principle concern is the examination of fuel elements used in the present reactors. These elements are usually of large dimension. Examinations are necessary at different stages: (a) before irradiation (form of element, contact of canning, welds, etc.); (b) during irradiation in loops in the reactor Pegase (verification of the geometry and state of the apparatus and the test element within the rig); (c) after irradiation (inspection of the result of the experiment - behavior of the fuel under irradiation, swelling, burst canning, etc.).

A permanent facility for neutron radiography has been built for the low powered reactor Peggy, 1 KW (the critical model for Pegase). It is used for studies to improve the sensitivity of the method for low intensity beams, and to aid thereby the eventual use of radioactive neutron sources. It also serves for ordinary neutron radiography of nonradioactive objects (the thermal flux is 1.7 x 10^5

---

(1) H. Rauch and G. Saringer, "Radiographic Inspection by Means of Thermal Neutrons," Materialprufung 8, 136 (1966).

(2) H. Rauch and K. Chountas, "Use of a Cone-Shaped Collimator for Neutron Radiography," (not published).

n/cm^2-sec). The principle of the conical collimator has been used with a length of 1 metre and an exposure diameter of 18 cm. The size of the inlet aperture is 1.8 cm. Objects are lowered to the collimator submerged under the pool by means of a vertical tube.

A third series of experiments has been carried out using the reactor Harmonie at Cadarache in collaboration with the private firm CSF (Compagnie general de telegraphie sans fil). The apparatus studied consists of a boron loaded conversion screen, an image intensifier system and an output phosphor screen of Type P11. A Polaroid camera was used to record the images using a thermal neutron flux of about 2×10^5 n/cm^2-sec. Further studies are envisaged with improved tubes.

CENTRE D'ETUDE NUCLEAIRES
Grenoble, France
J. P. Barton

Studies continue of the possibility of using accelerator and radioactive neutron sources for radiography. In particular it has recently been demonstrated here that satisfactory quality gamma insensitive (activation transfer) neutron radiography can be achieved under practical conditions with a typical 10^{11} n/sec output small accelerator source. Collimation demonstrated has been sufficient to distinguish 1 mm details in the middle of an object 60 mm thick. At the present time five different specific applications are under consideration, each of them sufficiently important that each user can envisage the purchase of a typical 10^{11} n/sec output accelerator neutron source especially for radiography.

Consideration of the possibilities of using radioactive neutron sources has led to the conclusion that Americum 241-Beryllium (recently becoming available as a by-product of reactor power programs), is at present a potentially useful source considering all aspects (portability due to low gamma emission, economic aspects, etc.). Experiments with a 3 curie Am 241-Be source at Grenoble have demonstrated that quite useful quality direct exposure neutron radiography can be performed with acceptable fast neutron and gamma interference, and with collimation sufficient for inspection of 1 mm details in the center of about 60 mm objects.

J. P. Perves

Neutron radiography continues to be in routine use for the inspection before, during and after irradiation of all types of in-core experiments in the open core materials testing pool reactors Siloe and Melusine. The underwater conical collimator system continues to prove both highly useful and highly convenient. Using this principle a similar but larger system is being installed in Siloe (15 MW-to be raised to 25 MW later this year). This will provide radiographs of size 30 cm by 40 cm in a single exposure, this being the important length of typical irradiation rigs.

Some initial experiments on cold neutron radiography using an existing beam from the low powered model reactor Siloette (100 KW) gave some very encouraging results. Using the dysprosium activation transfer process, one percent sensitivity was found for a thickness of 9 cm of steel (hole diameter = thickness = 0.9 mm on source side of steel) and it was apparent that the sensitivity was limited only by the collimation of the existing beam. Nylon threads down to 600 microns diameter could also be seen through 9 cm of steel with this beam collimation.

CENTRE D'ETUDE NUCLEAIRES
Saclay, France
J. L. Boutaine

In collaboration with the development of neutron radiography at Grenoble and elsewhere, studies are continuing - particularly of possible industrial applications outside the C.E.A. and also the possible usage of radioactive neutron sources. In the last few weeks a large

Americium 241-beryllium (33 curies) neutron source has been purchased for neutron radiography studies. With a half life of 458 years and costing about $15,000 this arrived by air from the U.S.A. Provided with the necessary shielding for shipment it is remarkable that such a source is reasonably portable and may well find useful applications on site as well as within the laboratory.

M. Farney

A neutron radiography facility has now (March, 1967) been installed on the reactor ISIS at Saclay. This is an underwater system and the principle of the conical collimator has been used as for the Grenoble reactors. The length is 120 cm and the exposure position diameter is 15 cm. Three different systems are available for holding the objects in the exposure position, and nonradioactive or highly radioactive objects of different shapes and sizes may thereby be accommodated. The reactor ISIS is a model reactor for the pool research reactor OSIRIS, and is joined to it by a water canal system. Experiments irradiated in OSIRIS may therefore be radiographed using the ISIS facility, without extraction from the shielding water and whether OSIRIS is at power or shut down. The neutron flux at the equivalent position of the collimator entrance beside OSIRIS is 2.10^{14} n/cm^2-sec when operating at 50 MW; ISIS originally operating at 250 KW may now be operated at 1 MW.

COMPAGNIE GENERALE DE TELEGRAPHIE SANS FIL

Domaine de Corbeville (Essonne), France

An image intensifier for thermal neutron radiography has been developed and tested using neutron beams from reactors at Saclay. A report giving details has been prepared by the company, it is dated July, 1966 and entitled "Convertisseur d'image porer neutrons thermiques." The company, which has experience in different types of image intensifiers used in X-radiography, is interested in further development of such apparatus for neutron radiography.

GENERAL ELECTRIC COMPANY

Irradiation Processing Operation
Pleasanton, California
C. R. Porter

G.E. has established a commercial neutron radiographic service at the Vallecitos Nuclear Center, Pleasanton, California. G.E. is now offering firm price quotations for industrial quality neutron radiographs upon request. Standard X-ray film sizes up to 14 x 17 inches can be routinely provided with a 24 hour turn-around from receipt of samples to return of samples with negative and positive prints.

Two beam ports provide large beams with a neutron divergence of less than 2 mils per inch with a thermal flux of about 10^6 n/cm^2-sec. One port and facility is used solely for examination of highly irradiated nuclear fuel elemenets or capsules up to 10 feet in length and 5 inches in diameter taken in 15 inch segments. A second beam port provides the capability for radiography of all types of unirradiated materials with a nearly gamma free beam up to 24 inches in diameter.

The radioactive material facility is in heavy use for interim and post-irradiation examinations. The non-radioactive facility is being used for neutron radiography of explosive devices revealing details not obtainable by conventional X-ray techniques.

For further information or application data contact Bruce Meyer at G.E., IPO, P. O. Box 846, Pleasanton, Calif.; or call (415) 862-2211.

LOS ALAMOS SCIENTIFIC LABORATORY

Los Alamos, New Mexico
B. L. Blanks, D. A. Garrett and R. A. Morris

Recent activities at the Los Alamos Scientific Laboratory in the field of neutron radiography have been application oriented. Prior research has been devoted to the development of a high resolution neutron imaging system. The results of this work will be presented at the Fifth International Conference of the Society for Nondestructive Testing to be held in Montreal, Canada.

Applications of neutron radiography to problems of a practical nature include (a) detection of hydrogenous seals in steel valves, (b) detection of voids and discontinuities in metal encapsulated high explosives components, and (c) water and oil contamination detection in weapons components.

PRINCETON UNIVERSITY

School of Engineering and Applied Science
Princeton, New Jersey
J. Grey and R. Moss

The construction of a neutron radiography facility at the Industrial Reactor Laboratories is nearing completion. A 15 cm neutron image intensifier has been obtained from the Rauland Corporation. The object of the program will be to study boiling heat transfer of water in a metallic wick structure using neutron radiography.

TOKYO SHIBAURA ELECTRIC COMPANY

Central Research Laboratory
Kawasaki, Japan
S. Kawasaki

A neutron television system has been used to observe motion patterns of water in a 60 mm steel tube. This system is set up at the No. 2 beam port of the TTR-1 reactor. The beam intensity is 2.5×10^5 n/cm^2-sec with a cadmium ratio of 3.5. The multi-stage image intensifier has a neutron-photon converter containing a 4:1 mixture of natural LiF and ZnS(Ag). The gain of the intensifier is 5×10^4. We are now experimenting with a 10^{11} n/sec (14.1 MeV neutrons) Cockroft-Walton type of neutron generator, hoping to take advantage of this type of source for economic reasons. The moderator system will use the Be(n,2n) 2He reaction in order to thermalize quickly and in order not to decrease the available neutron intensity.

MEETING REPORTS

This is a special section for this Newsletter. It reflects the increased neutron radiographic application and development activity and the corresponding increase in which neutron radiographic papers are presented at conferences.

Neutron radiography will be represented at an international meeting in May, 1967. The following papers are scheduled for presentation at the International Conference on the Utilization of Research Reactors and Reactor Mathematics and Computation, to be held in Mexico City, May 2-4, 1967:

"Neutron Radiography as a Research and Development Tool at the Nuclear Test Reactor," by J. C. Carver and C. R. Porter (G.E., Vallecitos, U.S.A.).

"Use of the Siloe 15 MW Research Reactor," by M. Merchie (CEA, France).

The paper, "Methods for Neutron Image Detection," H. Berger (Argonne) is scheduled to be included in a Radiation Session at the 1967 Annual Meeting of the Society of Photographic Scientists and Engineers, to be held in Chicago, May 14-19, 1967.

The program for the American Nuclear Society, 13th Annual Meeting in San Diego, California, June 11-15, 1967, lists two neutron radiography papers. These are:

"A Track-Etch Plastic-Film Technique for Neutron Imaging," H. Berger and I. R. Kraska (Argonne).

"High Resolution Neutron Radiography Using Pulsed and Steady-State Reactor Sources," J. R. Shoptaugh, Jr., and W. L. Whittemore (General Atomic).

Two papers concerned with the neutron radiographic inspection of explosive devices are to be included in the Fifth Symposium on Electro Explosive Devices (EED's), June 13 and 14, 1967, at The Franklin Institute Research Laboratories, Philadelphia. The papers and the organization concerned with them are:

"Neutron Radiography Inspection of Ordnance Components," McDonnel Co., and Argonne National Laboratory.

"Neutron Radiography in Quality Control of EED's," G.E. Co. (Pleasanton, Calif.).

Two neutron radiography papers are now being prepared for presentation at the 1967 National Fall Conference of the Society for Nondestructive Testing, to be held in Cleveland, Ohio, Oct. 16-19, 1967. These are:

"Neutron Imaging Techniques," by S. P. Wang (Rauland Corp., Chicago).

"On Optimizing an Sb-Be Source for Neutron Radiographic Applications," by D. C. Cutforth (Argonne, Idaho).

CALL FOR PAPERS

A neutron radiography session is now being organized for the 1967 Winter Meeting of the American Nuclear Society, to be held in Chicago, Nov. 5-9, 1967. One session emphasizing neutron radiographic applications is assured; additional sessions can be scheduled, if necessary. For further information on this ANS meeting contact Leslie Burris, Jr., Argonne National Laboratory, Argonne, Illinois 60439.

SPECIAL REPORT ON THE FIFTH INTERNATIONAL CONFERENCE ON NONDESTRUCTINE TESTING

This meeting will be held in Montreal, May 21-26, 1967. Neutron radiographic papers now known to be accepted for presentation at the conference are the following:

"Improved Resolution Neutron and Radiography," B. L. Blanks, D. A. Garrett and R. A. Morris (Los Alamos, U.S.A.).

"Applications of Neutron Radiography Using a Pool Reactor," W. A. Carbiener (Battelle, U.S.A.).

****

NUMBER 7. 1967

ACCELERATORS INCORPORATED

P. O. Box 3139
Austin, Texas 78704, U.S.A.
N. A. Bostrom (President)

Neutron radiography development work is planned. The Picker nuclear generator will be used.

ALDERMASTON, A.W.R.E.

Berkshire, England
B.E. Huggins (SRI/RMS Building B.2.03)

Neutron radiography is being used by this nondestructive testing section at this research laboratory. Applications include the examination of boron content in mixed plates. The neutron beam is from the 5 MW HERALD research reactor.

ATOMIC ENERGY OF CANADA, LTD.

Commercial Products
P. O. Box 93
Ottawa, Canada
W. E. Downs

A study of neutron radiography is planned. Particular interest is in the use of SB^{124}-Be neutron sources.

BATTELLE MEMORIAL INSTITUTE

Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201, U.S.A.
B. K. Hajek (text received 10/21/67)

In operation for over two years, the neutron radiography facility at the 2 MW Battelle Research Reactor is being used for surveillance of all types of reactor fuels experiments before, during, and after irradiation. Radiography of specimens, irradiated both at the BRR and at other reactor sites, has increased to an average of two jobs per week. Radiographs are obtained routinely of specimens up to 10 feet long and 1.5 inches in diameter with images of long specimens composed of several 12-inch sections.

A 12-foot long, 1.5 inch square collimator provides a thermal neutron flux greater than 10^8 n/cm^2-sec for radiography and specimens are scanned past the collimator at a constant speed. All handling of specimens is done underwater.

Under consideration is a collimator design which incorporates the advantages of both Soller slits and conical shape. The collimator will provide a higher neutron flux and a wider field to increase the versatility of the facility.

Additional information may be obtained from Brian Hajek at the above address or call (614) 299-3151, Ext. 30232.

BILBAO LABORATORIES DE ENSAYOS E INVESTIGACION INDUSTRIAL

Bilbao, Spain

News has been received from Professor F. Albisu, Head of the Departamento de Technologia Nuclear at the above address. A program of investigations in neutron radiography started in June of this year using the ARBI reactor. Those concerned with the investigations are Professor M. J. C. de Zabalo (director of Center), Professor F. Albisu and Dr. M. S. Torre Enciso. Beam characteristics have been measured on various vertical and horizontal beams. A beam from the thermal calumn has been selected. Various cadmium divided collimator systems have subsequently been studied, measuring the collimation and the degree of uniformity of the flux.

CENTRE D'ETUDES NUCLEAIRIES DE CADARACHE

Department Des Piles Experimentales
B. P. No. 1, Saint-Paul-Lez Durance,
B-DV-RH, France
C. Desandre (text received 10/22/67)

The main program at Cadarache involves the inspection of fuel elements before, during, and after irradiation. The sources of neutrons used are the PEGASE reactor (35 MW) and the PEGGY reactor (critical mock-up 1 KW). In the PEGGY reactor a permanent testing device is used for systematic inspection of the different types of fuel used in the French power reactor program (metallic U, UO_2 and UC carbide). This has reached a routine stage. It is planned to increase its capability by a modification of the conical collimator.

In PEGASE, inspections of fuel are performed during its irradiation in heavy rigs. A second permanent neutron radiography facility has been designed and will be built for the beginning of next year. Examination of very large annular fuel elements (77 x 95 x 540 mm) (i.e. 21 inches long) has been successfully performed.

A program to study biological applications of neutron radiography is being started using the PEGGY reactor.

CENTRE D'ETUDES NUCLEAIRES DE GRENOBLE

B. P. 269
Grenoble 38, France

Since the last newsletter a study has been started within the accelerator section to investigate the problem of obtaining a high thermal neutron flux using neutron generators. Monsieur Mouraille is conducting these thermalization studies, and it is hoped the results will be of use to neutron radiography.

The original small concial collimator system has been moved back from the SILOE reactor to the MELUSINE reactor. The larger, more complex facility is scheduled to be installed this month in the increased power SILOE reactor.

CENTRE D'ETUDES NUCLEAIRES DE SACLAY

B. P. No. 2, 91. Gif-sur-Yvette, France
M. Barny and M. Boutaine

Application studies have been underway using the ISIS neutron radiography facility. A problem of water drops entering in front of the detection screen has been overcome. A second more advanced radiographic facility is being designed for the 50 MW OSIRIS reactor, based on the divergent collimator principle. Experimental studies are in hand for very high intensity Sb^{124}-Be systems activated and manipulated under water.

DOUNREAY EXPERIMENTAL REACTOR ESTABLISHMENT

Thurso Caithness, Scotland
I. C. Hendry and A. R. Spowart (IMTR Technical Group)

First accounts are available of neutron radiography development at Dounready (TRG Report 1440(0)(1967) and AERE R5456, pp. 39-65).

A 1 inch diameter horizontal beam hole from DMTR (now 22 MW) has been in use since 1964. The first collimator used was a single parallel tube. This was later replaced by a bundle of small diameter steel tubes, but problems were attributed to critical reflection of neutrons. A third system included cadmium arrangements to overcome neutron reflection, but melting of the cadmium near the reactor core was experienced. A fourth system consists of an aluminum tube with cadmium aperture. Neutron radiography exposure cells capable of handling active test rigs have been used.

The Mark III facility planned for operation from early 1968 will feature capabilities of: (a) 10^5 MeV Curies, (b) objects 7 ft 6 in long, 7 in diameter, (c) viewing windows, (d) handling devices, (e) purge facilities, (f) TV viewing system. Applications include radiography of fusible allow thermometers. Hollow, enriched, fuel pellets have been examined. Individual particles can be seen in UC/SiC dispersed fuels. A direct viewing system based on a neutron scintillator and an image intensifier is being tested. Future plans include studies of epithermal neutron radiography.

GENERAL ATOMIC

P. O. Box 608
San Diego, California 92112, U.S.A.
W. L. Whittemore and J. R. Shoptaugh, Jr.
(TRIGA Reactors Facility)

The possibilities of stop-action or "flash" neutron radiography using a pulsing TRIGA reactor have been investigated, and found to offer promising possibilities for studies such as boiling liquids or biological neutron radiography where motion exists. Using a TRIGA Mark I with a vertical 16 foot beam tube useful neutron radiography may be performed in a single pulse. The time duration is such that the burst width at half power is 15 m sec, and the dose received at the screen is 6×10^7 n/cm^2. Improvements on this can be envisaged.

Studies of high resolution neutron radiography have been undertaken. The use of single emulsion fine grain photographic film gives improved resolution with thin gadolinium foil direct exposure techniques. Cracks and interruptions as small as 0.001 inch are easily detected with this technique.

GENERAL DYNAMICS

Fort Worth Division
P. O. Box 748
Fort Worth, Texas 76101, U.S.A.
W. E. Dungan

A memo has been received from the above address describing neutron radiographic work initiated in these laboratories. The report is entitled "Neutron Radiography of Polyurethane Foam Materials." It contains eight figures, many of them photographs, and cannot therefore be reproduced in entirety in this newsletter.

To summarize very briefly the report describes the neutron radiography facility used, a 6 in. by 6 in. in-core beam tube of the Reactivity Test Assembly (RTA), employing a multi-slit Soller type collimation half way along its length. A series of test blocks of polyurethane have been studied with a range of thicknesses and a range of artificial voids. It is concluded that the small holes can, in fact, be revealed by neutron radiography. The importance of correct exposure is emphasized. Material grain formed in the fabrication process is also vividly revealed by the neutron radiographs.

GENERAL ELECTRIC COMPANY

Vallecitos Nuclear Center
Pleasanton, California 94566, U.S.A.

Neutron radiography application work is being performed at these recently available, commercial facilities. A brochure is now available describing the General Electric facility, and some reports of work have appeared elsewhere, e.g. Product Engineering, July 17, 1967, pages 81 and 82.

KAMAN NUCLEAR

Garden of the Gods Road
Colorado Springs, Colorado 80907, U.S.A.

The application of 14 MeV neutron generators to fast neutron radiography is being studied. The required yield of 10^{10}-10^{11} neutrons/second is available from either pumped accelerators or sealed-tube generators. Radiographs were taken with a collimator of 2.2° total aperture, a flight path of 5 meters, an exposure time of 15 minutes, and a neutron output of 4×10^{10} neutrons/sec. Thus the neutron fluence incident on the exposure area was 8×10^6 n/cm^2 over a circular area 19 cm in diameter. A radiograph of a transformer and a circuit board showed the gap between the transformer frame and core and gaps between windings, rows of potentiometers with shafts visible, small transformers on the board and their mounting hardware, four rows of connectors on the board, and a few small components. Standard X-ray film with an X-ray intensifier screen were used. Applications of the technique are being sought, and suggestions would be very welcome. Future plans include extension of the neutron generator technique to thermal neutron problems.

MEDICAL COLLEGE OF GEORGIA

Augusta, Georgia 30902, U.S.A.
M. Brown et al.

Neutron Radiography at the Medical College of Georgia and the Savannah River Laboratory (Du Pont): This summer, a group composed of personnel from the radiology department of the Medical College of Georgia (W. P. Lawrence and M. Brown) and members of the experimental physics group of the Savannah River Laboratory (P. B. Parks and G. F. O'Neill) began a project to investigate potential medical applications of neutron radiography.

Preliminary work prior to beginning this project served to confirm the work of others and enabled us to develop techniques using thermal and epithermal neutrons. We are now in the process of constructing suitable anti-scatter grids for near thermal radiography and are developing plans for a detection system which will enable us to study the applications of fast neutrons for radiographic purposes using voids for contrast.

OAK RIDGE NATIONAL LABORATORY

Oak Ridge, Tennessee, U.S.A.

Interest has developed in neutron radiography and a facility has been designed for the ORR reactor. The design is based on the divergent collimator-under water principle as described in the British Journal of Nondestructive Testing, Vol. 8, No. 4, p. 79-83, 1966. Initial applications will be irradiation rigs.

OREGON STATE UNIVERSITY

Radiation Center
Corvallis, Oregon 97331, U.S.A.
C. R. Porter (text received 10/30/67)

The Oregon State University's Radiation Center can now be added to the list of operating neutron radiographic facilities. We have installed, in a tangential beam port of our TRIGA Mark II, a neutron aperture/gamma shield cast from a special Pd-In-Cd alloy. The double conical aperture is a separate insert and is easily interchanged with those of different diameters. A 0.250 in. dia. aperture gives, with a 110 in. aperture, to film distance, a beam divergence of approximately 2-1/4 mils/inch. With this aperture an exposure time of 40 minutes gives a uniform density of 2-1/2 on type F film using a Research Chemical flame sprayed, infinite Gadolinia backscreen. The beam diameter is 10-3/4 in. The beam appears to be very soft with a minimum of gamma contamination.

Sophisticated in-port shielding and a near aperture-plane internal shutter allow a minimum of external shielding around the beam box. Shutter action times are less than 1 second and access to the beam box is possible within two seconds after shutter closure.

The radiographic beam source is located at the inner end of another beam port. By varying the material in the inner section of this port, we expect to be able to exercise considerable control over the spectral shape of the radiographic beam.

At the moment we have two grants, one from the Office of Naval Research to investigate medical neutron radiography and one from the National Science Foundation to investigate diffusion processes in glass using radiographic techniques. Of course we are always cooperating with a variety of people in applying neutron radiographic techniques to solve diverse problems.

The pulsing capability of our TRIGA will permit such useful techniques as in-vivo radiographs of biological objects. The exposure time in this mode is approximately 1/100 second.

PRINCETON UNIVERSITY
School of Engineering and Applied Science
Princeton, New Jersey, U.S.A.
R. Moss (text received 10/10/67)

The construction of a neutron radiography facility at the Industrial Reactor Laboratories has been completed. Photographs taken directly of the screen of a 15 cm image intensifier show that resolutions of 0.016 have been achieved. Processing the film with a photodensitometer enables one to determine the exact thickness of water penetrated to ±0.006 inches for thicknesses up to 0.125 inches. Using this facility analytical work on the fundamental boiling processes that take place in a porous medium during heat transfer has now been experimentally verified.

ROCKETDYNE
A Division of North American Aviation, Inc., Materials and Processes Production Metallurgy Unit, Dept. 596-175, Zone 17, Rocketdyne, Canoga Park, California, U.S.A.
D. J. Hagemaier

Various nondestructive test methods have been considered for threaded joint inspection on start tanks. The feasibility of titanium hydride detection by neutron radiography has been established. Control specimens were radiographed using the General Electric Nuclear Laboratory facilities at Pleasanton, California. In some specimens slight formation of titanium hydride was detected at the interface between hydrogen and helium tanks. These results were confirmed on sectioning. Further work is planned.

UNIVERSITY OF BIRMINGHAM
Department of Physics
Birmingham, England
M. R. Hawksworth and L. Holland (text received 10/1/67)

Work on the determination of the "characteristic curves" of many film/intensifying screen systems is now complete and a report is in the course of preparation. The fastest systems were found to be those using granular screens of the Stedman type and X-ray film. "Threshold speeds" of $(2 \times 10^4\ n/cm^{-2})^{-1}$ have been measured. In general, characteristics differ to some extent, in n-radiographic applications, from those quoted by the emulsion manufacturers for other conditions of use.

The theoretical optimization of small source/moderator systems is also nearing completion. In most cases the peak thermal flux is typically a factor of 100 to 1000 below that of the source strength, e.g. for the specific case of a ^{241}Am/Be source of intensity 10^7 n. s^{-1} in a light water moderator the peak thermal flux is 2×10^4 n. $cm^{-2}s^{-1}$. This should provide, incidentally, a usable radiographic beam of 10-100 n. $cm^{-2}s^{-1}$, enabling radiographs to be obtained after exposure times of 1000s under favorable conditions.

U.S. NAVAL WEAPONS STATION
Quality Evaluation Laboratory
Concord, California, 94520 U.S.A.
H. Heffan

This laboratory has reported interest in neutron radiography, particularly in the possibility of small source techniques -- using accelerators or isotopic sources.

WOOLWICH ARSENAL
London, S.E. 18, England
R. L. Durart (Nondestructive Testing Section)

This laboratory is interested in neutron radiography. Some initial experiments have been performed using a 5.5 MeV X-ray machine and a beryllium target as the source of neutrons.

WRIGHT-PATTERSON AIR FORCE BASE
Air Force Institute of Technology
Ohio, 45433, U.S.A.
A. R. Bauer

The neutron radiographic beam at the Air Force Nuclear Energy Test Facility has been put into preliminary use. Work is underway to eliminate some nonuniform intensity areas in the beam.

****

NUMBER 8. 1968

ACCELERATORS, INC.
P. O. Box 3293
Austin, Texas 78704, U.S.A.
N. A. Bostrom

Design of a collimator and moderator for use with a 150 KV accelerator is in progress.

AEROJET-GENERAL CORPORATION
P. O. Box 77
San Ramon, California, 44583, U.S.A.
P. E. Underhill

Aerojet-General Corporation, has recently added a neutron radiography facility to its existing 250 KW (Th) research reactor located at San Ramon, California. This facility is at present capable of exposing a 6-inch diameter area, and will soon be enlarged to a 22-inch by 28-inch area for exposure of 14-inch by 17-inch film to a thermal neutron flux of 10^7 n/cm^2-sec. The facility is available for commercial use. For prices and further information please contact the above address.

ARGONNE NATIONAL LABORATORY
Idaho Falls, Idaho, U.S.A.
D. C. Cutforth

The new Sb-Be source designed for neutron radiographic inspection within the laboratory Fuel Cycle Facility is undergoing preliminary tests prior to inserting the source in the facility. The Sb source is metal, instead of the oxide used in previous tests, and its activity is estimated at 6000 curies. Initial radiographs with the new source show a H and D density of about 2 for dysprosium transfer to a medium speed X-ray film (Kodak AA) with saturation exposure and decay periods. It is expected the new source will be placed into the Fuel Cycle Facility in May 1968.

ATOMICS INTERNATIONAL
Division of North American Aviation, Inc.
8900 De Soto Avenue
Canoga Park, California 91304, U.S.A.
N. M. Ewbank

Atomics International has been engaged in routine quality assurance testing of ordnance, using the Shield Test and Irradiation Reactor (STIR), during the past year. Twenty 11 x 14 inch neutron radiographs (transfer technique) are made in a single fifteen-minute reactor exposure. Frequently, twelve-foot long, single piece radiographs are made during the same fifteen-minute exposure. All work is performed in an open air shield test room under ambient conditions.

Exploratory neutron radiographs have been made for studies of solid propellant rocket motor grains, reactor fuel elements, boron fibers in both aluminum and titanium matrix composites, organic bonded honeycomb assemblies, silver and soft soldered joints, circuit boards, integrated circuits, and irradiation capsules. Both positive and negative color neutron radiographs have been prepared using three different converter techniques; the significance of this work is still under consideration.

Weekly "off-hours" classes in neutron radiography and film interpretation are being conducted. A Saturday seminar type class for interested persons who must travel long distances is under consideration.

ATOMINSTITUT DER OSTERREICHISCHEN HOCHSCHULEN
Schuttelstrasse 115, A. 1020
Wien, Austria
H. Rauch and M. Manoussakis

Investigations of the H.-diffusion in solid and liquid materials by means of neutron radiography and the hydrogen-deuterium (H-D) method are carried out. The measurements are carried out with water, glycerine and similar compounds at various temperatures. Osmotic and biological processes are also under investigation with this method. The pulsed operation of the reactor is used for the observation of rapidly varying processes. A paper giving results is in print for "Atomkernenergie," see below.

BATTELLE-NORTHWEST
Pacific Northwest Laboratories
P. O. Box 999
Richland, Washington 99352, U.S.A.
C. B. Shaw

To the present time this laboratory has been working with isotopes. Reactor designs suitable for our radiographic applications are being evaluated.

BETTIS ATOMIC POWER LABORATORY
Westinghouse Electric Corporation
Box 79
West Mifflin, Pennsylvania 15122, U.S.A.
K. D. Kirk

The quality control department at this laboratory is beginning to investigate neutron radiography and neutron transmission techniques for production use to verify fuel zone loading in pelletized fuel rods. Image intensifier techniques have been tried, with satisfactory results, using a reactor beam. Serious interest is being shown in non-reactor neutron source possibilities and the purchase of a suitable neutron generator is being considered.

BOEING COMPANY
Wichita Division
Wichita, Kansas 67210, U.S.A.
E. N. Perry

The application of neutron radiography to the inspection and evaluation of cured adhesives and polymers has been studied at the Wichita Division for more than a year. A program is underway to adapt neutron radiography and neutron viewing to a regular production line inspection system. The continuation of this development is justified by the promise of a multi-million dollar application in the airplane/aerospace industry alone.

For many years there has been a need for a nondestructive method that would allow a critical examination of the bond line in a cured metal bonded part. The conventional NDT methods have so far fallen far short of this requirement. An earlier attempt using neutron radiography had failed in 1960, because a suitable source of thermal neutrons was not available. Typical bond line thicknesses of laminates average about 3 mils with a minimum that approaches 1 mil. Excellent neutron radiographs have been produced by one minute exposures of such laminates, and equally good results have been obtained for honeycomb sandwich construction. The technique has been extended to other polymers, and to other elements in applications that utilize the "difference in cross section concept." Neutron radiography of such thin layered samples is an accomplished fact, and most thicker samples have proven to be less troublesome.

The economic utility of the neutron imaging precept is dependent on the development of a dynamic viewing system. This development program will include a study of neutron sources, i.e., emitters, generators and reactors, and also the development of a direct viewing system. Such a direct image forming capability is needed for the dynamic scanning of large bonded assemblies, several hundred square feet in area. The desirable features for such a system include a large area of view, sufficient contrast to minimize eye fatigue and a resolution comparable to the bond line thickness. The immediate goals are to evaluate the most promising neutron sources and the proposed methods for neutron imaging. Qualified participation in these studies is invited.

BOEING COMPANY

Missile and Information Systems Div.
Aerospace Group
Seattle, Washington 98124, U.S.A.
L. W. Dahlke

Interest in neutron radiography exists at this laboratory. A neutron radiography facility is being set up at the local University of Washington reactor, and the use of accelerator sources at Boeing will be considered.

CENTRE D'ETUDES NUCLEAIRES

Saclay, France
J. L. Boutaine

Neutron radiography application work is now being carried out in collaboration with different industries. Meanwhile application research is being performed; one topic being studied is that of brazings. The arrangements for studies of the 33 curie Am-Be and larger quantities of Po-Be have just reached the operational stage.

EURATOM

CCR, Ispra, Italy
J. P. Valentin

We have finally started in the practical development of a neutron radiography device for post-irradiation examination of experimental fuel elements.

As the work has to be performed in a hot cell, and because of the experimental conditions, we have selected the use of an accelerator as neutron source.

Investigations are presently performed with the manufacturers to determine the optimum characteristics for the machine, target, moderator and collimator system, and also to define some economics parameters. We hope to make operational this installation for the second half of 1969.

GEORGIA INSTITUTE OF TECHNOLOGY

Nuclear Research Center
Atlanta, Georgia 30318, U.S.A.

This laboratory has started a program in neutron radiography. M. E. McLain, Jr. will be responsible for setting up neutron radiography facilities on the 1 MW research reactor. J. J. Allen is planning research into biological applications of neutron radiography. W. H. Wilkie is planning research on aspects of fast neutron radiography.

GREYRAD CORPORATION

61 Adams Drive
Princeton, New Jersey 08540, U.S.A.
J. Grey (President)

Greyrad has simulated the flow of hydrozine through a rocket chamber's catalyst bed, and taken high-speed motion pictures, via neutron radiography, of the resulting flow processes and patterns.

Neutron radiographs have been utilized for the examination of plastic die-castings while still inside their dies.

A report has been prepared entitled, "Neutron Radiography Facility." This 34 page report, Bulletin GB-4, Jan. 1968, describes the facility and details a particular engineering application.

GULF GENERAL ATOMIC INCORPORATED

P. O. Box 608
San Diego, California 92112, U.S.A.
R. M. Watkins

The first session of a new series of neutron radiography training courses was held March 25 to 29 at the Gulf General Atomic Laboratories in San Diego, Calif.

A full class of ten participants took part in this intensive program which included both lecture and laboratory work. Each of the students had the opportunity of preparing radiographs of samples brought from their own laboratories.

The new Rauland Corporation image intensifier system was demonstrated in conjunction with the Gulf General Atomic TRIGA reactor facilities which were used as the neutron source for the experimental work.

INSTYTUT BADAN JADROWYCH

Warsaw, Poland
M. Radwan

A neutron generator, Type T (dn), has been received. The tritium targets have an activity of 12 curies and a diameter of 14 mm. The 14 MeV neutron output is 1-5 x 10^{10} n/sec. Neutron radiography and activation analyses work is under consideration.

MEDICAL COLLEGE OF GEORGIA

Augusta, Georga U.S.A.
M. Brown

and

SAVANNAH RIVER LABORATORY

Aiken, South Carolina 29801, U.S.A.
P. B. Parks

Since the last newsletter, we have continued our work in low energy, neutron radiography of biological media. Antiscatter grids have been built with a grid ratio of 15.6/1 and 77 opaque lines per inch. The use of these grids has greatly extended the usefulness of neutron radiography in such small animal applications as arteriography and ventriculography. The principle problem still requiring work is the reduction of the penumbra that is caused by the rather large source dimension which we have used.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Plum Brook Reactor Facility
Sandusky, Ohio 44870, U.S.A.
L. A. Thaler

Neutron radiographs have been obtained utilizing the Underwater Beam Room Facility at the NASA 60 MW Plum Brook Reactor. The collimator utilized is 292 cm long, 4 cm wide and 12 cm high. Collimation of 7 min. of arc in the horizontal plane is obtained by means of 9 nickel strips running along the length of the duct. A traversing mechanism was used to drive the object to be radiographed across the 4 cm wide beam. The radiograph obtained showed no evidence of the nickel strips.

A facility for underwater neutron radiography has been designed and is being built. Initial application will be surveillance of reactor experiments before and after irradiation.

RAULAND CORPORATION
5600 W. Jarvis
Chicago, Illinois U.S.A.
S. P. Wang

The capabilities of the latest neutron image intensifier system have recently been demonstrated at the following four laboratories: Atomics International, General Electric Company, Gulf General Atomic Inc., and Los Alamos Scientific Laboratory.

TOKYO SHIBAURA ELECTRIC COMPANY, LTD.
1 Komukai Toshibacho, Kawasaki-Shi
Kanagawa-Ken, Japan
S. Kawasaki

Progress is reported in using a special neutron generator for neutron radiography. The accelerator has a much higher neutron output than previous models (a factor of ten) and is used in conjunction with a multi-stage image intensifier system (gain of 10^4).

UNIVERSITY OF MICHIGAN
Department of Nuclear Engineering
Ann Arbor, Michigan, U.S.A.
M. J. Flynn and G. Knoll

Our project is currently moving forward in three areas:

(1) A thermal neutron radiographic facility is presently being designed specifically for biological applications. A divergent collimator placed vertically in the pool of the Ford Nuclear Reactor (2 MW swimming pool reactor) will be employed along with a film detection system.

(2) Our interest in fast neutrons is continuing with some basic experiments planned as early as possible with the Nuclear Engineering Department's fast neutron generator in anticipation of a facility designed specifically for medical applications.

(3) Analytical studies of the six techniques outlined in Memo (1) is being continued. The medical center at the University Hospital has continued with their basic interest and has recently become involved in two areas: A. the development of a xerographic detection system for neutrons such as has been successful in mamographic X-ray studies, and, B. studies under the Cancer Research group on "The Detection of Neoplasms in Bone with Neutrons." Dr. Kittleson of the Radiology Department is currently serving as project advisor for the medical center.

UNIVERSITY OF PALERMO
Sicily, Italy
W. Leotti

Research in neutron radiography is being planned at this University. The project will be supervised by Professor M. Carmelo.

WESTERN NEW YORK NUCLEAR RESEARCH CENTER INC.
Buffalo, New York, 14214, U.S.A.
R. F. Lamb (Director)

The center is operating a prototype research reactor under steady state and transient conditions, and is interested in the condition of UO_2 pellets within the pin and also in dimensional changes in the envelope. Mr. P. T. Burnett, Operations Manager, is primarily responsible for the present effort to set up a neutron radiography facility and to ascertain the feasibility of getting the required dimensional changes.

****

NUMBER 9. 1969

A.E.R.E. HARWELL

Didcot, Berkshire, England
G. Constantine

We have been working in the neutron radiography field recently at Harwell and have installed a working unit in LIDO, our pool reactor of 200 KW max power. The collimator transverses the biological shield and is 7 ft long. This is a cadmium lined conical hole in borated wax, starting at 3 in x (0 in - 1/2 in) variable slit, and opening out to 4 in diameter at the radiography station where the thermal flux is up to 4 x 10^6 n/cm^2-sec. So far we have carried out some basic investigations into resolution problems using the transfer technique, since our initial terms of reference were neutron-radiography of active experiments from our MTR's. We have also neutron-radiographed a number of specimens for interested parties in the UKAEA and industry through our recently formed NDT Centre.

The LIDO building has inadequate crane capacity for handling active experiments from the MTR's so we have built a facility in DIDO for this side of the work. This should give a flux of 2 x 10^7 n/cm^2-sec with an aperture of 1 in x 1/4 in. Again it is a conical collimator, though this time it can be flooded and has a lead door at the outer end. It should be in operation before the end of the year.

We have also designed an underwater unit for LIDO comprising a collimator and watertight cassette running on vertical rails attached to the LIDO core support structure. The LIDO core moves around the pool to serve irradiation facilities one at a time. This unit could make use of LIDO's spare neutrons wherever it is, rather than demanding exclusive use of the core during the radiography session. This will be cheaper and better for short notice work too. Whether we build it will depend on the demand for neutron radiography and whether the DIDO unit will be able to meet very stringent background restrictions for frequent operation. These restrictions are imposed by adjacent experiments where low background is imperative. Space for additional shielding does not exist.

Dr. Peter Iredale of our Electronic and Applies Physics Division has been carrying out experiments on a scintillator-image intensifier set-up aimed at high resolution capability.

AEROJET GENERAL CORPORATION

P. O. Box 77
San Ramon, California 44583, U.S.A.

Aerojet General Corporation's Nuclear Division will give a course in Neutron Radiography at San Ramon, California on 3, 4, and 5 February 1968. Enrollment will be limited to 10. Enrollment fee will be $150.00.

Purpose of the course is to provide basic information on the methods, capabilities, and applications of neutron radiography as a nondestructive inspection technique and a valuable complement to x-radiography. The course should be of particular interest to those in the field of quality assurance, quality control, and nondestructive testing.

Participants in the course will perform neutron radiography using the 250 kw(th) AGNIR reactor which provides a uniform 10^7 neutrons/cm^2-sec beam of thermal neutrons over a 30-1/2 by 22 in rectangular cross-section exposure area.

The course, which is to be presented four times a year, is the fourth given by Aerojet.

Attending the most recent course were personnel from Aerojet-Delft; Battelle Northwest Laboratories; Edwards Air Force Base; Lockheed, Sunnyvale, California; McClellan Air Force Base;

Thiokol Chemical Corporation, Huntsville, Alabama.

ARGONNE NATIONAL LABORATORY

Argonne, Illinois 60439, U.S.A.
J. P. Barton and H. Berger

A main theme of the experimental program at Argonne is to pursue the possibilities of using small (non-reactor) sources for neutron radiography. The sources previously studied at Grenoble (^{241}Am-Be and accelerators - Newsletters 4 and 6) have been extended at Argonne to include ^{241}Am-^{242}Cm-Be. Work is planned on sources of ^{252}Cf. The main conclusions of the ^{241}Am-^{242}Cm-Be study performed using a 10^9 n/sec source in hot cell facilities are: (1) Direct exposure neutron radiography is practical (graphs and figures are available relating source yield, collimation, exposure, image quality, etc.). (2) Transfer method neutron radiography is practical, but for a 10^9 n/sec source and using present simple detection methods - (Dy foil and KK film) - the beam collimation would be limited to 1:10 (aperture: length). Higher source strengths would, of course, allow correspondingly improved characteristics. (3) There is no apparent advantage to using beryllium-oxide rather than water as a moderator for Am-Cm-Be neutron radiography systems.

Application work using the 200 KW Juggernaut reactor continues on a routine basis. Epithermal neutron radiography has been used recently with very satisfactory results. This is particularly useful for examination of fast reactor fuel elements. The neutron radiography facilities on Juggernaut are being extended to provide improved collimation, larger exposure areas, variable collimation and, when appropriate, collimation of resonance energy neutrons. This makes use of the divergent collimator principle. Some work on image detection methods continued, and work on a standard quality test system is nearing completion.

ATOMICS INTERNATIONAL

(Div. of North American Rockwell Corp.)
P. O. Box 309
Canoga Park, California U.S.A.
N. M. Ewbank

Atomics International has continued the program of routine quality assurance testing of ordnance. Thus far approximately 6000 objects have been subject to controlled inspection and exploratory or procedural studies. A recent neutron radiograph of a boron fiber-titanium composite and an integrated microcircuit was made on Eastman Kodak Company high resolution plates. The images were enlarged 500X with good resolution and detail.

Image intensifier techniques have been investigated using fiber optic light intensifiers developed by E.O.S. The results have been good without interference from reactor "noise" that has been experienced in other systems.

J. O. Henrie:

Atomics International has prepared the preliminary design of a small nuclear reactor optimized for neutron radiography. Its fuel will be highly enriched uranyl sulphate contained in a spherical stainless steel vessel, similar to the 19 other homogeneous solution type reactors which have been built by Atomics International. It has been designated "Model L88" and contains many of the inherent safety and simplified operational features of the model L77 reactor. Other principal features of this reactor are:

1. Flux-to-Power Ratio: The core size has been optimized for maximum flux-to-power ratio and is physically smaller than any other homogeneous solution type reactor core. The reactor is designed to operate at thermal power levels up to 10 KW.

2. Gas Recombiner: To recombine the hydrogen and oxygen gasses which are produced by radiolytic decomposition of

water in the fuel solution, a new "condenser type" gas recombiner has been designed. It has no moving parts. The gasses are forced through the catalyst by a pressure differential sustained by condenser action. The entire recombiner, including catalyst and condenser, is to be constructed integrally with the reactor core.

3. Shielding: The basic reactor assembly will include a solid reflector and "shutdown" shield which is approximately 5 ft in diameter and 6 ft high. This assembly would be shipped to the building site and placed in a concrete shield having a thickness of 3-1/2 to 5-1/2 ft, depending on density and hydrogen content of the aggregate selected. The basic assembly can also be water shielded.

4. Flux Trap: The core contains a removable flux trap which can be filled with beryllium or other materials to provide an intense source of neutrons. The use of different materials in the flux trap provides some control of the neutron spectrum and gamma ray intensity of the emerging beam. By properly shaping the flux trap material, the neutron flux in the beam at the target area can be flattened.

5. Beam Facilities: As many as four separate horizontal beam facilities can be conveniently provided around the reactor. The basic conical shape of these beams can be altered by changing the size and location of removable apertures. Moving the aperture closer to the flux trap increases the width or angle of the beam but reduces reflector effectiveness. Increasing the size of the hole in the aperture also increases the width of the beam, but provides poorer "neutron optics." Analysis of a typical setup shows that with the reactor operating at 10 KW and with an object being radiographed 100 diameters from the aperture, the collimated thermal neutron flux at the object is 1.0 x 10^7 n/cm^2-sec.

For further information on this reactor for neutron radiography, please contact Mr. J. O. Henrie.

BATTELLE-NORTHWEST
Pacific Northwest Laboratories
FFTF Project
P. O. Box 999
Richland, Washington 99352, U.S.A.
W. S. Chenault

A contract was let to provide facility requirements and the conceptual design of Neutron Radiography Equipment for the Fast Flux Test Facility (FFTF) which will also meet the requirements of the Argonne National Laboratory Hot Fuel Examination Facility (HFEF). General Electric, Vallecitos, was selected June 1968, as performer. A Phase I report will be issued December 1968 by T. A. Fredricks, to include a survey of neutron radiography technology as present day "state of technology," and to analyze results of survey for applicability to FFTF applications, and recommend necessary verification tests.

CENTRE D'ETUDES NUCLEAIRES, GRENOBLE
B. P. 269
Grenoble 38, France
G. Breynat, VuHong Lac, H. Berger *et al*.

This account relates to work within the two sections, Section des Accelerateurs and Section d'Application des Radioelements. Several associated programs are currently under way using some of the various accelerator neutron sources under the direction of Madame Breynat. One program is concerned with an investigation of film emulsions and scintillators which will yield improved relative neutron-gamma response for accelerator produced thermal neutron beams. Work on these programs is being carried out by Mr. D. Giloppe and Mr. J. Berthod, respectively. Another program, conducted to collaboration with ISPRA, Italy, is concerned with the optimization of an accelerator technique for the neutron examination of irradiated fuel materials in a hot-cell. Both thermal and fast neutron techniques are being considered.

In the SAR, Mr. Vu Hong Lac is conducting a program to determine the optimum use of small accelerators for neutron radiography. Thermalization studies have been made and continue. Best results thus far involve a combination of heavy water around the target and a surrounding light water moderator. Heavy materials such as Pb and U immediately surrounding the target are being investigated as a means for decreasing some gamma radiation and for enhancing the neutron yield by (n,2n) reactions. Comparisons of thermal neutron radiographs with fast neutron radiographs yielded from the program described below are being made.

A comparison program in SAR is being carried out by H. Berger, during a planned one year visit to CENG. The study is concerned with detection methods for fast neutrons. It is hoped that, once good image detection methods for fast neutrons are known, then a realistic evaluation of fast neutron radiography can be made. Detection methods under study include x-ray film techniques with scintillators, threshold detectors such as phosphorus and sulfur, and track-etch techniques. Preliminary results have confirmed reports by others that simple techniques involving x-ray fluorescent screens and suitable x-ray film can yield useful results for some applications, even though the results are truly gamma and neutron radiography involving many energies of both radiations. With fast films and screens, exposures in the order of 10^7 n/cm^2 yield good film densities.

CENTRE D'ETUDES NUCLEAIRES
DPE/SPE, Saclay
B. P. 2, 91 Gif-sur-Yvette, France
G. Farny

(a) Reactor OSIRIS: A neutron radiography facility was installed at Saclay in August. This is for the reactor OSIRIS, a high flux reactor which is now being increased in power level from 50 MW to 70 MW. The underwater collimator is of the divergent type, with length 220 cm and exposure area 60 cm by 15 cm. The inlet aperture is of variable dimension to allow compensation for flux changes due to irradiation experiments within the reactor core. Water is displaced from the exposure position by a jacket and gas pump system. The top seal of the jacket is made, after positioning of the object, by forming a collar of ice. Freon is used for the cooling, and the process takes only some 15 minutes. Using the divergent collimator and these methods all sorts of capsules and loops may be radiographed conveniently in single exposures.

(b) Sb-Be Neutron Sources: Good neutron radiographs have been obtained with a system based on 6,000 curies of Sb-Be. The flux at the divergent collimator entrance aperture was 8.5 x 10^8 n/cm^2-sec, and the quality of the radiographs remained satisfactory throughout the first six months without replenishment of Sb. A similar arrangement will be constructed in a hot cell at Cadarache for the examination of low enrichment irradiated fuel. (Editors note: The editor wishes to apologize for any confusion resulting from the mention of 100,000 curies Sb-Be in previous Newsletters. The possibility of using these high intensity sources has not been exploited.)

(c) TV System: Because of industrial demands for examination by neutron radiography of numbers of objects in series a TV system is under development using an external beam from the TRITON reactor. The need for an image intensifier has been avoided thanks to the recent development in France of a hypersensitive camera which has a threshold at about 0.1 ml. Improved scintillator converters have been prepared in the laboratories and, due to the high reactor flux available, we have been able to work with very thin scintillator sheets and obtain good fine grain picture outputs of strength 50 ml, well above the camera threshold.

GENERAL DYNAMICS

Fort Worth Division
P. O. Box 748
Fort Worth, Texas 76101 U.S.A.
W. E. Dungan

Our work in neutron radiography during the past year has been concerned primarily with surveying applications pertinent to our inspection and quality control programs. We have recently completed modifications of the test facility to upgrade our capability in this area, e.g., increase of maximum reactor power from 100 watts to 1 kilowatt, and beam tube optimization for collimating quality and useful area exceeding 1 ft^2.

One noteworthy application using neutron radiography is the inspection of the interior of sealed hydraulic control valves for rubber O-ring placement. Some of these O-rings have teflon back-up rings which are not readily observed by the radiographs; the relative location of the rubber O-rings, however, verifies the presence or absence of these back-up rings. X-ray inspection of these parts yielded negative results.

We will have a complete report of our efforts published at the end of this year.

IDAHO NUCLEAR CORPORATION

Box 1845
Idaho Falls, Idaho 83401 U.S.A.
L. G. Miller and G. E. Stokes

Idaho Nuclear Corporation is developing a neutron radiographic capability at the Materials Testing Reactor (MTR). This service will be available for the many irradiation sponsors at the Test Reactor Area. At present we have a temporary facility using a small thermal column hole with 10^{11} n/cm^2-sec neutron source over a 4 x 4 inch area. Neutron radiographs are taken 20 feet from source with uniform neutron flux over an 8 x 8 inch area. The nearly pure thermal neutron flux at the object position is 4 x 10^6 n/cm^2-sec. Neutron radiographs have been made of several irradiated fuel pins and many nonradioactive samples. The permanent facility should be ready for use within a year. Neutron radiographs up to 15 x 24 inches will be possible.

LOS ALAMOS SCIENTIFIC LABORATORY

P. O. Box 1663
Los Alamos, New Mexico 87544 U.S.A.
D. A. Garrett and R. A. Morris

14 MeV Neutron Radiography: Experiments are in progress to develop a 14 MeV neutron imaging system. The imaging method is based on the detection of fission products induced by 14 MeV neutrons in ^{235}U and ^{238}U imaging foils. The paths of the fission products are recorded by placing a quartz plate in contact with the imaging foil during exposure. The fission tracks are made visible by etching the exposed quartz with hydrofluoric acid. The etched plate is read with a computer-coupled optical scanning system. Quartz is employed as an imaging plate because of the low background compared with that observed on some of the conventional di-electric films.

This system will be applied to 14 MeV neutron imaging in cases for which the track density does not exceed 10^4 n/cm. The computer will be employed to derive a numerical image from the input data.

L. Forman and D. A. Garrett

Energy-Resolved Neutron Radiography: Experiments are in progress to develop an energy-resolved neutron radiographic system. The system will be applied to the inspection of individual components of a composite matrix. Neutrons having energies corresponding to the resonance energies of the components are selected for imaging.

Neutrons from a pulsed neutron source are selected in energy by time-of-flight techniques. A TV image tube is gated to accept neutrons of the desired energy or energy range. Preliminary experiments are in progress using a fast burst reactor with a 10 meter flight path. The yield of this reactor is approximately 10^{17} n/burst.

R. A. Morris

Materials Contrast Sensitivity Measurements: A series of investigations has been initiated which are designed to measure the sensitivity of a neutron radiographic system to changes in object thickness and composition. For the purposes of these experiments, contrast sensitivity has been defined as the ratio of the percent change in transmitted neutron intensity through an object to the percent change in object thickness. Contrast sensitivities have been measured for aluminum, steel and graphite. System characteristics such as detector sensitivity and neutron energy spectra are included in the parametric analysis.

The results of the experiments will be employed to define an empirical relationship between the experimentally observed contrast sensitivities and neutron cross sections of the materials under investigation.

NUCLEAR TECHNOLOGY CORPORATION

116 Main Street
White Plains, New York 10601 U.S.A.

Nuclear Technology Corporation has available a compact, low-cost, swimming pool type reactor designed specifically for neutron radiography applications. The reactor is located near the bottom of a pool approximately 20 feet in depth and 8 feet in diameter. The fuel is fully enriched uranium-aluminum plates clad in aluminum, and the fuel loading is 1.5 kg of U-235.

Neutron radiography may be performed underwater by means of a horizontal collimator located adjacent to the core or above the pool with a vertical collimator. A well collimated neutron beam suitable for neutron radiography can be provided with intensities up to 10^8 n/cm^2-sec.

The reactor also has application to neutron activation analysis and the production of short-lived isotopes.

SAVANNAH RIVER LABORATORY

Aiken, South Carolina 29802 U.S.A.
and

MEDICAL COLLEGE OF GEORGIA

Augusta, Georgia U.S.A.
P. B. Parks and M. Brown

We have continued to develop new processes to improve the applicability of neutron radiography to the visualization of biological tissues. Our studies have been organized along two topics: Improvements in slow neutron radiography to increase the contrasts seen in soft tissue, and development of a fast neutron radiographic facility.

The slow neutron work has centered about the use of heavy water (D_2O) to induce tissue deuteration. Muscle and bone have been shown to be easily deuterated whereas fat and other hydrocarbons show little tendency to deuterate. The deuterated tissues are quite transparent to neutrons compared to the non-deuterated tissues. We have obtained several radiographs of biological specimens in which the fatty structures such as marrow and fat pads stand out very clearly. Such delineation of fat in a neutron radiograph of normal tissue is impossible. A program to study the biological effects of a short term deuteration procedure is under way at the Medical College with Dr. Sherwood Reichard as principle investigator.

A prototype fast neutron rectilinear scanning facility has been constructed from three basic components: a Texas Nuclear 14 MeV "Neutron Generator," a Picker "Magnascanner," and a moderately efficient fast neutron detector of the Hansen-McKibben type. Several scan type radiographs have been taken with the facility. The spatial resolving power of this instrument is, of course, quite poor, but investigations are under way that may make substantial improvements in the resolving power possible.

STATE COMMITTEE ON ATOMIC ENERGY, MOSCOW
G.K.A.E., Stardmonetnii, Per. 26
Moscow 180, U.S.S.R.
N. D. Tyufyakov and S. Shtan

Studies of Detectors for Neutron Radiography: Methods for the preparation of our first samples of luminescent screens were essentially similar to the technology of the preparation of x-ray screens. The improvement consisted in the purification of all intial materials, in the introduction of $MgCl_2$ into the mixture, in the change of the temperature of calcination and the method of the introduction of boron into the scintillator.

If the calcination temperature was raised to 800°C then there occurred an increase of the sensitivity of the screen against slow neutrons. Efficient purification enables us to control the dosage of added mixture of other elements to the scintillator. The effect of the load of scintillator upon the sensitivity of the screen for neutrons was investigated. At a flux of 10^4 neutrons/cm^2-sec the density of the blackening of a 1.5 x-ray film of the type RM-1 in a combination with such screens is attained in an integral flux of $\sim 5 \times 10^5$ neutron/cm^2. The image possessed a mottling which was caused apparently by the technology of the preparation of such screens.

Since the efficiency of metallic screens (convertors of the neutron image) depends on a great number of factors, the experimental elucidation of the part played by each of them is difficult. We carried out therefore an analytical investigation of the effect of the macroscopic cross-section of the interaction of neutrons with the nuclei of the screen material, of the energy of the secondary radiation, of the screen thickness, of the spectrum of slow neutrons, etc. upon the efficiency of such screens. The correlations obtained were used for the numerical calculation of the flux and secondary radiation current for the front and rear screen. The results have been prepared in the form of analytical expressions and graphs which enable a choice of the optimum screen thicknesses for given control conditions.

Neutron Sources for Neutron Radiography: A series of experimental neutron sources has been prepared on the basis of isotopes of transuranium elements Pu^{238}, Cm^{244}, Cf^{252}. The neutrons were obtained from the (α,n)-reaction or from the spontaneous fission of nuclei. The targets used in the (α,n)-sources were Be, B, Li. The neutron yield of the individual sources was equal to $5 \times 10^6 - 5 \times 10^8$ neutrons/sec. A description of the design of sources has been prepared and the energy distributions of fast neutrons are reported. An estimate has been made for the possibility of the construction of isotopic (α,n)-sources with a yield of 10^9-10^{10} neutrons/sec, which are required for the neutron radiography in other investigations. A comparative estimate is given for expedient fields of the application of different types of neutron sources for radiography. The advantages of isotopic neutron sources and of small-scale neutron generators with sealed tubes have been considered.

Generation of Collimated Beams of Slow Neutrons from Isotopic Neutron Sources: A method has been developed for the measurement of the energetic composition of slow neutron beams by means of scintillation counters with single crystals of LiI which possess equal forms, dimensions and packing, and which are enriched by Li^6 and Li^7-isotopes, respectively. A pair of such crystals of a certain thickness is used for each energy interval. The splitting into intervals is determined by the crystals used. This method was used for the study of the effect upon the characteristics of the beam of slow neutrons of the following factors: diameter of the collimator channel, distance between the source and the channel bottom, moderator layer above the source, Cd-plating of the channel walls and the energy composition of the neutrons from the source. The measurements have been carried out in a water tank. The collimators were prepared from drawing paper impregnated with paraffin and from steel sheets. The diameter of the collimators was varied stepwise from 20 mm to 100 mm. The geometric collimation angle was constant during the measurements. We used isotopic neutron sources Pu^{239} + Be, Pu^{238} + B, Cf^{252}. Analytical estimates and experiments show that the flux of thermal neutrons in the collimated beam is directly proportional to the flux at the base of the collimator which has to be positioned in the maximum of the distribution of thermal neutrons in the moderator. A Cd-plating of the collimator walls at a distance of 3-4 diffusion lengths from the collimator base is unsuitable. All investigated dependencies have been tabulated and presented in graphs.

U.S. NAVAL ORDNANCE LABORATORY
White Oak, Silver Spring
Maryland 20910 U.S.A.
P. W. Hesse

Thermal neutron radiographs have been obtained at this laboratory using a 400 KV ion accelerator and a T-D reaction in conjunction with L^6F screens and fast medical film. The moderator consists of a lead, paraffin and boral shield with a cadmium tube. Resolution and sharpness were only fair as expected from the fast components, but gradations in a Masonite step wedge could be seen. Plans are being made to use local reactor facilities.

****

#10. 1969

ACCELERATORS
P. O. Box 3293
Austin, Texas 78745 U.S.A.
F. A. Iddings

Dr. Frank A. Iddings is again consulting with Accelerators, Inc. for the summer. He will be working on improvement of moderator design, collimator design, and radiography quality. Application of the equipment to specific industrial problems has begun. Inquiries of a specific nature are welcome.

In addition to the 150 kV machine, higher voltage (300-600 kV) machines will be utilized in this summer's work. Other nuclear reactions for neutron production will be examined.

Plans are made to couple the present system to Rauland's image intensifier system this summer. This would provide a completely instrumental neutron radiography system of reasonable size and cost.

ARGONNE NATIONAL LABORATORY
Argonne, Illinois 60439 U.S.A.
J. P. Barton

Experiments have been undertaken to check the feasibility of using californium-252 for thermal neutron radiography. The source was of strength 3.4 x 10^8 n/sec (equivalent to 141 µg) when the first trials were started in April. Thermal neutron radiographs have been obtained with quality comparable to those obtained previously with ^{241}Am and ^{241}Am-^{242}Cm-Be sources. In addition to the foreseeable economic advantage for ^{252}Cf the main technical advantages for neutron radiography seem to be (1) the good ratio of fast neutron yield:peak thermal flux (a ratio of 75 has been measured for our source in water moderator) and (2) the small size of the source for possible fast neutron radiography.

A method for increasing the efficiency of the direct exposure scintillator-film radiographic technique has been demonstrated. Gains of 300 percent are possible by a simple cooling procedure and this could be of particular value in small source neutron radiography.

A quantity of data has been accumulated on preliminary standard test systems. A general discussion of an introductory nature is included elsewhere in this Newsletter.

Initial studies have been undertaken to see if we should move the neutron radiography program at Argonne from the Juggernaut reactor to the CP-5 reactor. Advantages include more economic deployment of Argonne facilities, and a considerable increase in peak source flux. Difficulties include the necessity to perform both application (fuel development) and research programs on a single beam, and the problem of operating on a crowded reactor very near to experiments demanding a low and steady background. Experimental trials are being initiated to see if we can extract a suitable beam along an evacuated flight-tube, pass the beam within inches of neighboring experiments and operate in a special building extension outside the containment shell.

ASTON, UNIVERSITY OF ASTON IN BIRMINGHAM

Dept. of Physics, Gosta Green
Birmingham 4, England
A. J. Cox

Some work has been performed on neutron thermalization with small sources and neutron howitzers. This program is continuing with a study of the neutron spectrum produced by such a device. First work covers the thermal region, and some resonance sandwich foil studies have been undertaken using the D-T reaction with a 150 KV SAMES accelerator and a howitzer arrangement. A time of flight technique is being developed and it is hoped to study the howitzer performance with D-D neutrons.

BABCOCK AND WILCOX

R&D Division
P. O. Box 1260
Lynchburg, Virginia 24505 USA
W. R. Gibson

Babcock and Wilcox Co. has designed a collimator for use with the Babcock & Wilcox Test Reactor (BAWTR). The collimator is currently being fabricated and is expected to be in use by June 1969. This facility is to be capable of exposing a 2-1/2 inch by 30 inch area. Its initial use will be the interim examination of fuel capsules being irradiated in the BAWTR.

BATTELLE NORTHWEST

Pacific Northwest Laboratory
P. O. Box 999
Richland, Washington 99352 USA
C. B. Shaw

Research has been initiated under the direction of the USAEC Division of Isotopes Development for study and development of a system using ^{252}Cf for neutron radiography. The purpose is to provide a useful, transportable, source for thermal to fast neutron radiography.

A theoretical evaluation of ^{252}Cf for use as a source for neutrons has been completed. The computer assisted analysis provided data regarding moderated neutron spectra for a given moderator thickness, resultant flux, and relative image foil response. The results predict optimum moderator thicknesses for a given image foil situation as well as providing selective moderation, hence spectra tailoring.

A prototype apparatus has been constructed and a 260 μgm ^{252}Cf source is being used to experimentally evaluate the analytical results.

Evaluation of PNL reactors for use in neutron radiography continues.

BILBAO LABORATORIES

de Ensayos e Investigacion Industrial
(Dept. of Nuclear Technology)
Apartado 1234
Bilbao, Spain
S. Torre-Encisco

Work has continued on neutrography possibilities with the ARBI reactor (Argonaut type, 10 KW). A Cd collimator 1.50 m long, 10 x 10 cm cross section has been installed in one of the thermal column holes (previously occupied by a graphite bar). The neutron beam so obtained has the following characteristics: thermal flux, 1.5 x 10^6 n/cm^2 sec (at 1

KW reactor power); Cd ratio, 33; neutron/gamma ratio, 1.6 x 10^6 n/cm /mR^{-2}. More than 500 neutrographies have been carried out, using various screens (Cd, Ag, Au, Gd, In). A report in two parts is being published and the first one is now available.

BIRMINGHAM UNIVERSITY
Department of Physics
P. O. Box 363
Birmingham 15, England
M. R. Hawksworth and L. Holland

Reciprocity law failure studies on light emitting screen systems are nearly complete. The studies demonstrate that the empirical relation of Schwartschild is followed for exposure times (t) greater than 1 second (for beam intensities ϕ less than 10^5 n/cm^2-sec). Schwarzschild's relationship states that the effective exposure is ϕt^P where P is known as the "Schwarzschild Index" and is a characteristic of the photographic emulsion. A typical value for P is 0.74. This means that difference between the exposure time predicted to be necessary for a given task, with and without taking account of reciprocity law failure (P = 0.74 and P = 1.0) is some 500% for a reduction in beam intensity of a factor of 100.

BOEING COMPANY
Wichita Division
Wichita, Kansas 67210 USA
E. Perry

The application of neutron radiography to the nondestructive evaluation of organic adhesives and polymers in aerospace construction continues. Already proven desirable, the present effort is designed to establish an economical thermal neutron inspection station. The principal use will be the inspection of adhesive bonded honeycomb structures, but additional applications will include metal-to-metal laminates, metal-to-plastic and reinforced plastic composites. Applicable polymers include epoxy, phenolic, polyester, thiokol, silicone, and the urethanes.

A correlation study is in progress to illustrate the advantages of neutron radiography over other more conventional types of NDT. The principal test object is an aluminum honeycomb structure containing laminated aluminum skins, and five adhesive layers with a total bond line thickness in one area of 45 mils and 40 miles in the other locations. An extensive variety of bonding anomalies were programmed into this test assembly, and neutron radiographs have been made from both sides to show the location, size and shape of the adhesive defects. Size of the neutron radiographs is 14 in. by 17 in.

Comparisons of these neutron radiographs will be made with through transmission ultrasonic "C" scan charts; with low frequency ultrasonic "A" scan recordings; with laser holography; with 14 in. by 17 in. x-radiographs, and, with thermal nondestructive test methods. It is expected that these results will again show the unique ability of neutron radiography to locate and allow identification of adhesive defects inside metal parts, thus permitting a better judgement of the damage and the feasibility of repairs. Newly fabricated metal bonded parts, as well as in service components can be inspected on the airplane for bond quality and integrity of the unit.

Success of this program will revolutionize the nondestructive inspection of adhesive bonded structures and composites. The projected completion date is second half 1969, with follow-on applications programmed through 1972. It is now believed that suitable thermal neutron beams can be produced to make neutron inspection of thin organic cross sections economically competitive with other NDT methods. This achievement will provide much needed knowledge not now available without tear-up of the production part. More complete reports of these developments and applications of neutron radiography will follow.

DOUNREAY
Experimental Reactor Establishment
Reactor Group
Thurso, Caithness, Scotland
A. R. Spowart

The experimental program on optimizing the forms of both granular and glass neutron scintillators has been completed. This work has been published.

We have performed the first measurements of the absolute scintillation efficiency of a variety of granular and glass neutron scintillators using a specially selected/calibrated photomultiplier. The paper on this work has been accepted for publication in "Nuclear Instruments and Methods." Typical results were an efficiency of 9% for granular scintillator of 1 part LiF to 3.2 parts ZnS, and 0.45% for a 1 mm thick slice of glass scintillator containing 7% of Li^6.

Further work on measuring the gamma sensitivities and image resolution capabilities of these scintillators has been completed and is in the process of being published.

A. R. Spowart has been appointed as the Atomic Energy Authority's contact on neutron radiography with respect to the unclassified information exchange contracts with the U.S. Atomic Energy Commission and Euratom.

The present experimental program is concerned with the fast neutron radiography of nuclear fuels and optimizing moderator geometries for thermal neutron radiography.

This laboratory is now turning its attention completely from reactor neutron sources to the use of a sealed tube neutron generator of output 10^{11} n/sec of 14 MeV.

CENTRE D'ETUDES NUCLEAIRES, GRENOBLE
Service Des Piles, Cedex No. 85
38-Grenoble-GARE, France
J. P. Perves

Two under water-divergent collimator neutron radiography facilities are in routine operation for examination of irradiated systems. These facilities are on the reactors SILOE, 30 MW (with a 30 x 40 cm exposure area) and MELUSINE, 4 MW. Sealing to pump out the water around the object is provided by rubber or by freezing a collar of water with liquid nitrogen. In May 1969 a third facility has been added - an external neutron radiography facility on MELOSINE. This design incorporates a single crystal bismuth filter (15 cm) and is capable of variable collimation ratios within the range 140:1 to 400:1 (fluxes of 3×10^6 to 8×10^5 n/cm^2-sec). The exposure area is 23 cm in diameter. Direct exposure methods are possible and with gadolinium and single emulsion film considerable enlargement of the radiograph negative is possible. This external neutron radiography facility has been designed to satisfy industrial application needs. As from July 1969 the facility will be operational alternatively either with the thermal neutron technique or with the cold neutron technique. The cold neutron technique will be possible by insertion of a simple Be-Bi filter cooled by liquid nitrogen, and the whole operation of conversion from cold to thermal, or thermal to cold, will take about one hour.

CENTRE D'ETUDES NUCLEAIRES, GRENOBLE
Section d'Application des Radioelements
Cedex No. 85, 38-Grenoble-GARE, France
H. Berger

The fast neutron imaging study mentioned in Newsletter No. 9 has progressed so that some knowledge of several detection methods is available. Direct exposure methods with x-ray film with or without converter screens have yielded useful radiographs with both 14 and 3 MeV neutrons. Fluorescent screens with a fast x-ray film made for fluorescent screen use have yielded both the best speed and the best contrast of the direct film methods. A film such as Regulix HS with fluorescent screens such as Radelin Type TF requires a total neutron exposure of about 5 x 10^7 n/cm^2 for a useful result. Fast neutron images can also be prepared by two methods which are not sensitive to gamma or x-radiation. These are the activation, transfer method, and the track-etch technique. With 14 MeV neutrons, copper screens have yielded good fast neutron images with 30 minute irradiations in intensities as low as 5 x 10^6 n/cm^2-sec. Transfer detectors for 3 MeV neutrons are not as convenient to use, for reasons of physical form (best materials have been sulfur and phosphorus), longer half-life, and lower cross sections. However, some results at 3 MeV have been obtained with long exposures. The track-etch method is also gamma insensitive and has the advantage that it is capable of long integration time (as opposed to activation saturation problems for transfer detectors). Best results have been obtained with a cellulose nitrate material [Kodak-Pathe (France) Type CA 8015] exposed directly to 3 or 14 MeV neutrons, without an intensifier. Alpha particle and carbon recoil reactions in the plastic itself yield useful results for total exposures of 2 x 10^{10} n/cm^2. These detection techniques present a variety of characteristics and permit the potential of fast neutron radiography to be evaluated. At this point it can be mentioned that fast neutron radiography inspection of radioactive material (by either transfer or track-etch methods) is a possible application of the technique. Since it has also been possible to observe small thicknesses of low Z material in high Z assemblies (for example, 5 mm of rubber in 3 inches of lead) by fast neutron techniques, there may also be useful industrial applications of fast neutron techniques, with less problem for the neutron source than is the case for thermal neutron radiography. Further evaluation of fast neutron radiography is in progress.

GULF GENERAL ATOMIC, INC.

P. O. Box 608
San Diego, California 92112, USA
W. L. Whittemore

During the last several months the TRIGA Reactors Facility at Gulf General Atomic Incorporated has performed neutron radiography as a service. In addition to performing routine neutron radiography examinations of radioactive fueled thermionic cells, we have made special purpose examinations of a number of specimens. In several instances, this involved exploitation of neutron radiography to image hydrogenous material buried in large amounts of metal (e.g., "O" rings and plastic gaskets). In one interesting application of neutron radiography, a freshly prepared bone specimen was radiographed. The resulting image proved highly useful to correlate with an activation analysis investigation of the same specimen.

In the week July 28-August 1, Gulf General Atomic Incorporated is offering another Neutron Radiography Training Course. This course comprises five days of intensive study, including 12 lectures, 6 laboratory periods, and consultation on problems of special interest to individual students. The course is intended to equip the student to handle typical problems, perform the exposures, and interpret properly the results.

IDAHO NUCLEAR CORPORATION

Box 1945
Idaho Falls, Idaho 83401, USA
L. G. Miller and J. P. McNeece

A series of divergent collimators and resolution test objects are being used to determine the best method for universal resolution measurements and correlation of these measurements with a source diameter. Resolution figures of merit up to 500 are being studied using a relatively pure thermal beam.

Since many combinations of materials used in the reactor field are combinations of high and low neutron cross section materials, it is only natural to use neutron radiography as an analytical tool to determine the concentration and uniformity of these materials. As a first example, gadolinium in aluminum was tried in concentrations of 1% to 0.005%, indicating a straight line relationship between concentration and film density. We feel that low-resolution neutron radiography using a small neutron source could be used in the laboratory for many material combinations of reactor components, natural ore samples, etc.

Work is continuing on beam tailoring for contrast enhancement. With the first material, tantalum, a film density variation greater than 2 was accomplished between a thermal neutron radiography and a tailored beam neutron radiograph. Other materials are being tried as filter materials become available.

Design of a new facility is continuing. This will utilize the HG-9 beam hole in the MTR and greatly increase the present available neutron flux and resolution.

LEWIS RESEARCH CENTER - PLUM BROOK STATION

Taylor Road and Columbus Avenue
Sandusky, Ohio 44870, USA
L. A. Thaler

The Underwater Radiographic Facility at the NASA 60 MW Plum Brook Reactor has been operational since February of 1969. The collimator is a divergent type with a 3.175 cm square entrance aperture, a length of 457.2 and a viewing area 7.62 cm by 76.2 cm. The beam intensity in the viewing area is depending on the power and rod bank height of the reactor and varies at 60 MW from 2.5×10^8 n/cm^2-sec to 4×10^8 n/cm^2-sec.

The collimator is constructed of aluminum and is normally pressurized with helium when the reactor is operating and the quadrant is filled with water. The indium foil is encased in a water tight aluminum container which is slipped into a specimen holder. The holder has provisions for sealing lead type or non lead type specimens and can be pressurized for water removal and inserted at the collimator viewing area.

We are now using 5 mil indium foil and Eastman Kodak Type R, single coated, Industrial X-ray film and find that an NVT of approximately 2×10^{11} gives an excellent radiograph. A penetrameter is being made to our specifications so that we can determine precisely the resolution of our facility. To provide duplicate negatives we have been using Eastman Kodak Radiograph Duplicating Film (Estar Base).

Radiographs have been taken of various irradiated and non-irradiated fueled capsules and lead type capsules as requested by experiment sponsors. Periodic inspection of long term irradiations is in the program of one of our major experiments and indications are that neutron radiography will become a routine nondestructive test at this facility.

LONDON, UNIVERSITY OF LONDON REACTOR

Silwood Park, Sunninghill, Ascot
Berkshire, England
W. C. H. Alston

A neutron radiography program has been started using a facility set up on one of the weaker beam tubes, and useful radiographs have been obtained using the transfer technique with dysprosium foils. The in-pile collimator consists of a matrix of tubes with approximately 30 mins divergence (d/L). The facility itself is housed in a hydroboard block with a 5 in. x 5 in. x 20 in. sample port whilst the foils for exposure are held in a standard Ilford 1/2 plate (4-3/4 in. x 6 1/2 in.) photographic cassette with the lead backing plate removed. The facility is so designed that a small neutron chopper may be placed in the beam and the equipment also used for a neutron time-of-flight teaching experiment.

The facility has proved extremely useful for experimenters testing in-pile collimators used for neutron scattering experiments. It was possible to take profiles of the neutron beams energing from the collimators. From these, optimum dimensions for heavy metal shutters and other information important to the design of the neutron scattering rig were verified.

Plans are in hand for improvements to the existing set up. Sample and cassette ports of the above mentioned size are now available on the lower beam tube of the three-level neutron scattering rig. The neutron intensity here is a factor of 100 higher than on the initial arrangement. A collimator/shutter system is planned for this higher flux facility enabling further work to be carried out on improvement of resolution and enlargement of exposure areas.

PALERMO UNIVERSITY
Barcellona, Sicily
W. Leotti

A degree thesis has been prepared in the Italian language covering the field of neutron radiography. The work runs to fourteen chapters and considers the subjects of neutron sources, moderation, and detection. The particular objective was to plan a device for a swimming pool reactor and the last part of the thesis concentrates on this aspect.

CENTRE D'ETUDES NUCLEAIRES D.P.E./SACLAY
S.P.E., Boite Postale No. 2
Gif-sur-Yvette, Sein et Oise, France
G. Farny

(1) Underwater Facilities: Underwater neutron radiography of irradiation systems is now routinely performed on the reactor OSIRIS (50 MW). The earlier facilities on the adjoining low powered reactor ISIS are now used only on particular occasions. A new facility has been built for the pool of the reactor TRITON. Its objective, like that of the OSIRIS facility, is the neutron radiographic examination of irradiation experiments including fast reactor fuel development. The system of sealing by freezing a water collar gives satisfaction by its simplicity and efficiency.

(2) Industrial Applications: In addition to the above three neutron radiography facilities, a neutron radiography beam has been brought out of the 6 MW reactor TRITON (CEN Fontenay-Aux-Roses) to meet the needs of industry. This beam, which operates in air, is filtered by bismuth and is capable of direct exposure method neutron imaging. The number of demands for neutron radiography has lead us to pass a contrast with a firm already specializing in nondestructive testing (Qualitest) and this firm now runs the business. An automatic system for conveying objects is in fabrication, and with an exposure time of a few minutes (Kodak Type M film) the cost per neutron radiograph will be similar to that for a gamma radiograph.

SIEMENS AKTIENGESELLSCHAFT
Dept. ZFA 2WT, 8 Schertlinstrasse
8 Munich 25, W. Germany
A. Mosle

Theoretically there are various possibilities to apply neutron radiography in our research and development groups and investigations are just starting. Our first experiments made use of the Munich research reactor (swimming pool type).

UNIVERSITY OF TEXAS
Austin, Texas, USA
G. D. Bouchey and S. J. Gage

A facility using a 4 in. dia. vertical beam tube has been developed for routine thermal neutron radiography at the 250 kilowatt TRIGA Mark I nuclear reactor located at the University of Texas at Austin. Plans for utilization of the facility include routine applications in the area of nondestructive testing, particularly the inspection of explosive devices, as well as continued efforts to improve the quality of the radiographs that may be obtained (e.g., improved collimation schemes, variation of neutron energy spectrum, etc.).

ATOMINSTITUT DER OSTERREICHISCHEN HOCHSCHULEN - Vienna

Schuttelstrasse 115, A-1020
Wien, Austria
H. Rauch and M. Manoussakis

In continuation of work previously reported (Atomkernenergie 13 (1968) 444 - for translation see this Newsletter) we are making extensive measurements on proton diffusion in ice and water at various temperatures, and also on the proton diffusion in ice and water at various temperatures, and also on the proton diffusion from CH_3OH into CH_3OD and CD_3OD. In these substances the proton displacement is caused by the molecular diffusion and the jump mechanism of the protons between the molecules. By means of neutron radiography the mean displacement of the protons can be investigated and the two diffusion mechanisms can be separated. With this new method the proton exchange between plants and water is also under investigation.

****

#11. 1970

AEROTEST OPERATIONS

P. O. Box 78
San Ramon, California 94583 USA
R. L. Tomlinson

The Aerojet-General Corporation Neutron Radiography Facility is being set up as a separate operating unit from the Aerojet Nuclear Division, whose San Ramon, Calif. plant is being closed down. The Neutron Radiography Facility and the associated reactor operations, activation analysis, etc., will be known as Aerotest Operations and will continue to operate with its current staff using the Aerojet-General Nuclear Industrial Reactor (AGNIR) at its San Ramon, Calif. location. Short three-day courses in neutron radiography will continued to be given. Two such courses are currently scheduled, one in October 1970.

Aerotest will continue to offer commercial neutron radiography services at competitive prices. Current contracts are primarily oriented toward the ordnance device market; however, extensive development of the nonexplosive device market is being actively pursued.

ARGONNE NATIONAL LABORATORY

Argonne, Illinois 60439 USA
J. P. Barton and H. Berger

Experiments on californium-252 were started in April 1969, and technical results have been published in the AEC Californium-252 Progress Reports available quaterly from Savannah River Laboratory. Moderate quality neutron radiography has been shown to be possible with small ^{252}Cf sources.

A comment on the background to the program may be appropriate for the Newsletter.

In the view of many scientists, including Dr. Glen Seaborg, Chairman of the USAEC, the isotope californium-252 could prove very useful as a neutron source. The most likely methd for bulk production of the isotope is by successive build up by neutron capture in a spectrum optimized reactor. The lead time for production is long and the cost per milligram of the output will depend sensitively on the quantities produced. The table is taken from "Californium 252 Its Use and Market Potential" 1969.

Estimates of Maximum Production ^{252}Cf

	Mid 1970's	Late 1970's	Early 1980's
Grams/Year	5-10	20-50	40-250
$/Microgram	5- 7	2- 3	0.5-1.5

If the USAEC takes the decision to embark on a production program for californium-252 the neutron source could become available, after several years, at the attractive cost of 50 cents per μ gram (2.3×10^6 n/sec per μ gram).

The decision as to whether or not to embark on this program must be based on long range forecasts of the anticipated demand ten years or so in the future. Several types of application are being considered - neutron therapy, activation analysis, petroleum exploration, nuclear safeguards. The neutron radiography ^{252}Cf studies at Argonne are part of the AEC program to anticipate the future demand.

A preliminary survey, published by Crandall gives an estimate of demand for ^{252}Cf by the mid seventies. If the prediction is accurate, neutron radiography will involve over three million dollars worth of californium by 1975 (6 grams valued at the lowest figure of 50 cents/μg).

Work on standards is proceeding and a full paper on the subject will be submitted for the Cleveland neutron radiography session in October.

Track-etch detection studies have continued with particular emphasis on plastic detectors; both α-sensitive cellulose nitrate and fission fragment sensitive polycarbonate plastics. Thermal and fast neutron radiographic studies with these detectors are in progress. In both cases, sensitivity (i.e. the total neutron exposure required for a good resolution, gamma radiation free image) compares favorably with the transfer method. However, in both cases, low visual contrast remains a problem.

Recent studies on track-etch image enhancement have involved an electrical sparking method which yields a replica of the track-etch image on an aluminized Mylar film. Although this method continues to offer promise for track-etch autoradiographic images in which recognition of general shapes is important, several factors appear to limit the usefulness of this technique for enhancing more subtle radiographic images. Best results on image enhancement continue to be achieved here with photographic methods. It is hoped that image enhancement problems can be one major item of discussion at the track-etch sessions now being organized for the ANS Winter Meeting (Washington, D.C., Nov. 15-19, 1970).

Additional efforts on fast neutron radiography and neutron radiography directed toward biological problems are also continuing.

BATTELLE NORTHWEST LABORATORY

P. O. Box 999
Richland, Washington 99352, USA
J. L. Cason

A research program at Battelle-Northwest is being conducted to determine the usefulness of ^{252}Cf as a source for portable thermal neutron radiography. Emphasis has been in developing a device using ^{252}Cf that could be used for laboratory, hot cell or field radiography. Evaluation has been both analytical and experimental.

A 268 μg ^{252}Cf source (NS-1) was obtained from ORNL for experimental testing. This source has a yield of 6.2×10^8 n/sec and was used in an experimental container designed for NR.

A first generation portable neutron camera using ^{252}Cf as the source of neutrons has been constructed and is being used in studies for such applications as reactor fuel rod radiography, determination of polymer content and distribution in concrete and many other areas. Work to date indicates that a sufficient neutron dose (1×10^4 nv) can be delivered at the object position providing satisfactory resolution capability. A measure of success can perhaps be imputed by comparing the 4400 pound container in which the ^{252}Cf arrived at Battelle-Northwest with the 100 pound camera presently in use; or by comparing the experimental device which was restricted to use in a shielded facility with present use in a conventional x-ray laboratory.

The entire device including containment, moderation, collimation, and controls is portable. The camera can be operated manually, by use of batteries or with house current (110 V ac).

Work is proceeding to fully evaluate the physical properties of the fiberglass construction material for tensile strength, compressibility, thermal conductivity, etc. Work to be accomplished in the near future includes reducing the size and weight of the camera, designing neutron cameras for specific uses taking into consideration transport, environmental conditions, need for certain portions of the neutron spectrum and size of source material. Other work includes specific characterization of applications most useful for a portable device.

A BNW Technical Bulletin (BNWL-SA 3169) provides a complete summary to all work done with Cf-252 with specific references to other works by same author.

A Plutonium Recycle Critical Facility has been modified for providing neutron radiography of unirradiated samples. The PRCF is an experimental reactor designed to operate at maximum power level of 10 KW with plutonium or uranium fuels and either heavy or light water moderator. It is located in a cell below floor level and as such required special modifications to meet the requirements for neutron radiography (i.e., beam design, central flux trap and special shielding). The radiographic evaluation indicated that high quality neutron radiographs can be produced in reasonably short periods of time of both irradiated and non-irradiated samples (15 min. for Dy transfer, 5 min. for Gd direct). The thermal flux measured at the object position is 6×10^5 nv. Several collimator designs have been evaluated, both parallel and divergent. A special evacuated divergent beam was selected as providing optimum results (i.e., beam area, minimum geometrical unsharpness and maximum thermal flux (Ref. BNWL-UC-37).

<u>BOEING COMPANY</u>
Wichita Division
Wichita, Kansas 67210, USA
E. Perry

Thermal neutron radiography of adhesive bonded airplane parts has been compared with other NDT methods. Results were extremely good. Ultrasonic, holographic, thermal, microwave, and others were unsuccessful in finding many defects that were readily apparent in neutron radiographs of the same parts. Anomalies found by NDT methods other than neutron radiography remained unexplained as to type of defect, actual size and location, and significant effect relative to part integrity and service usefulness. Chief value of this comparison was the proof that neutron radiography can provide critical data not obtainable by other nondestructive means.

Until recently all successful neutron radiography of adhesive bonded metal parts was accomplished by reactor neutron sources. Now many good films of such parts have been made by the High Voltage Engineering Corp. using their Van de Graaff Accelerator. This exciting achievement provides some very practical advantages. Besides cost, these advantages are: 1. fewer requirements and regulations; 2. flexibility and portability of neutron source equipment, and 3. a dual switching capability for x-ray or thermal neutron radiography.

Such portability and radiation choice can permit inspection and analysis at the airplane, often without disassembly. Adhesive bond lines are inspected by thermal neutrons; metal components by x-ray, using the same machine. Conversion is rapid. Portability is by fork lift or bridge crane, as with the x-ray units already in use. Increased usage of bonded structures adds importance to these capabilities. Present costs compare with x-ray. Thermal neutron scanning systems will be cost competative with ultrasonic scan systems. Expect implementation in 1971.

DOUNREAY D.E.R.E., U.K.A.E.A.
Dounreay, Thurso, Caithness, Scotland
A. R. Spowart

The evaluation of the mobile NR equipment is continuing. The generator has been in operation for a total time of 60 hr at neutron outputs of between 10^{10} n/sec and 10^{11} n/sec.

Licensing discussions are taking place with organizations with a view to the equipment being manufactured commercially.

With a parallel tube collimator 7.5 cm diameter and 100 cm long, the peak collimated thermal neutron flux achieved has been 10^6 n/cm^2-sec, with an accompanying gamma flux of 9 R/hr. Typical exposure times are of the order of 100 sec with 1 mm glass scintillator and Royal Blue film to give a density of 1.5.

Preliminary trials with the image intensifier and granular neutron scintillator are most encouraging, but considerable further work has yet to be done in this area. The unit is already in use for routine detection of hydriding in zirconium and other work.

DOW CHEMICAL COMPANY
Rocky Flats Division
P. O. Box 888
Golden, Colorado 80401, USA
D. G. Vasilik and R. L. Murri

The Dow Chemical Company is presently operating a neutron radiography facility at its Rocky Flats Plant. Thermal neutron radiographs of excellent quality have been produced with a Kaman Nuclear, A-711, Neutron Generator (sealed-tube). A graphite moderator is used to thermalize the 14.3 MeV neutrons from a tritium target in the sealed tube. A maximum thermal flux in the moderator of 4.77×10^6 n/cm^2-sec has been measured.

GENERAL DYNAMICS
Fort Worth Division
P. O. Box 748
Fort Worth, Texas 76101, USA
W. E. Dungan

The 1-milligram Cf-252 source was received from the AEC Savannah River plant 19 February 1970. The source was contained in a 1-inch-wall lead cylinder which was shipped in a 30-inch diameter steel cask containing paraffin. The outside surface dose rate of the cask with source was about 600 total millirem of neutrons and gammas, requiring sole use of van for transportation. Upon arrival contamination checks were performed on the source capsule for several days to verify integrity of the source for leaks. A handling rod was attached to the source and a series of dosimetry experiments with health physics instrumentation, e.g., TLD gamma dosimeters, geiger, BF_3, and FND instruments were completed with the source in the shipping cask and suspended in air in the hot cell for foil measurements.

Upon completion of these tests, the source was suspended at the center of a 36-inch square stainless steel tank filled with water. Additional dosimetry tests, including gamma spectroscopy were recently completed for a variety of shielded configurations and materials. Materials used included lead and borated polyethylene. Results will be included in the first progress report being written and will be summarized in the next AEC information brochure.

Neutron radiography tests are being initiated immediately using divergent collimators in the 36-inch shielded water tank.

GRUMMAN AEROSPACE CORPORATION
Bethpage, New York 11714, USA
F. R. Swanson

Research at Grumman has included a feasibility study of using a three million volt Van de Graaff accelerator as a source of thermal neutrons for industrial inspection problems. This investigation has used the $Be^9(d,n)B^{10}$ accelerator source with various paraffin moderating assemblies, and has yielded encouraging preliminary data. A thermal flux of ∿10 (n/cm^2-sec) appears to be practical, at a resolution of 30 mils/inch (1-1/2" dia. x 50"), a cadmium ratio of 4.0 (Au foil, 30 mil Cd), and a flux-to-gamma dose of 4.0×10^5 (n/cm^2-mr). These radiographic conditions are based on a deuteron current of 300 μa at a beam voltage of 3.5 Mv. The ratio of "thermal source strength" to target yield appears to be about (1/50) for the present moderator optimization, and further neutron imaging work (Gd back foild on type AA film) are planned for the future.

HARWELL, A.E.R.E.
Research Reactor Division
Didcot, Berkshire, U.K.
R. S. Matfield

A neutron radiography unit has been installed in DIDO with a divergent collimator lined with cadmium. The source aperture is 1 in. x 1/2 in., the collimator length is 86 in., and the total distance source to foil is 115 in. The collimator ratio is therefore 230:1 in the horizontal direction, as used for precise width measurements of samples held parallel to the major axis. The cadmium liner is over the full length of the collimator, but the collimator stops at 42 in. short of the tank end of the beam hold in order to keep the cadmium from overheating.

The extremely well thermalized beam is 3-1/2 in. diameter and has an intensity of 5×10^7 ncm^{-2}s^{-1} at the foil. The out-of-pile shielded unit is fitted with a manipulator and is designed to accommodate active rigs and fuel elements. The manipulator is used for rotating active rigs into position prior to making an exposure. It is a device with three rubber covered wheels, disposed at 120° intervals, which can be adjusted until they grip the outside of a vertical, cylindrical rig. One of the wheels is remotely operated and this is used to turn the rig.

Applications so far have included the examination of rigs and fuel capsules, the assessment of hydrides in zirconium and steel, boron carbide in zirconium, and gadolinium oxide in magnesium. The integrity of resin and rubber bonds has been checked and cooling passages in turbine blades examined.

Work on the dimensional measurement of samples within active rigs has been reported, and a creep rig fitted with an image-enhancement device is being irradiated. The use of this device allows the swelling of a pressure tube to be periodically measured to ±0.0015 in. when the rig is unloaded during reactor shutdowns. Current work includes the evaluation of the "track etch" technique using boron/cellulose acetate and uranium glass.

An improved collimator has been designed which will have removable beam-forming inserts and annular cadmium discs to limit multiple reflections. A uranium neutron booster can be fitted to the in-pile end and this will allow epithermal and fast neutron studies. This equipment will increase the beam size at the foil to 8 in. diameter.

A 3000 curie antimony-beryllium mobile source unit has also been designed and should be operational early in 1970.

HELSINKI TECHNICAL UNIVERSITY
Department of Technical Physics
Otaniemi (Helsinki) Finland
H. Reijonen

At the reactor Laboratory of the Institute of Technology, Helsinki, Finland, we have worked with neutron radiography for about a year.

We started with conventional direct-exposure methods, that is Rh-Gd and Gd metal foils and NE 425 scintillators combined with Kodak x-ray films Grystallex and Inductrex.

At the thermal column of our reactor, TRIGA MK II operating at 250 KW we have constructed a beam with the following characteristics: $\phi_n = 8 \times 10^5$ n/cm^{2}s ϕ = 2,3 R/h, (Maxwellian spectrum, T_m = 20°C) half angle divergence = 0,5°, picture area 10 x 10 cm^2. Also a cold-neutron beam, Emax 5 MeV, 5 x 10^5 n/cm^{2}s has been successfully used for neutron radiography of steel containing hydrogenous materials. Soon we will also have at our disposal a γ-free beam, 10^8 n/cm^{2}s.

The following problems have been studied using neutron radiography:

- Hydrogen in Zr and Ti welds;
- Biological applications of neutron radiography;
- Distribution of lubricants in a rotating bearing;
- Observations of the solidification of Sn-Cd alloys.

We are now selling neutron-radiography applications to the Finnish industry and contracts have been made with two firms for nondestructive quality checking (brazed joints, glued steel-doors, etc.).

In the future we will continue working with neutron radiography. We are considering building a neutron TV-system in the gamma free beam. Also we have plans to test radioactive reactor fuel elements. One scientist is hired by the Finnish Atomic Energy Commission to work with neutron radiography.

HIGH VOLTAGE ENGINEERING CORPORATION

Burlington, Massachusetts 01803, USA
A. D. Fussa

The Boeing-Battelle-High Voltage Engineering program to develop an industrial accelerator source for neutron radiography indicated that the Be^9(d,n)B^{10} reaction contains the most essential properties. Briefly the properties are:

1. Neutron yield of the beryllium is constant, whereas the tritium and lithium targets deteriorate during use.

2. Beryllium targets are low cost and safe to handle, whereas tritium is expensive and radioactive and lithium is chemically reactive.

3. Beryllium target yield has a thermal neutron ratio of approximately 200, whereas the 14 MeV neutrons from tritium are 1000, a factor of five poorer.

From the first of the year, a great deal of effort has been devoted to optimizing the target design, moderator, and collimator. The accelerator portion is a standard product, requiring no development.

Collimators have progressed through three phases:

1. 2 in. diameter output L/D = 12, 2 in. input.
2. 4 in. x 5 in. output L/D = 15.
3. 8 in. x 10 in. output L/D = 18 or 36.

Our excellent results have demonstrated resolution, contrast, and definition approaching that provided by a reactor. Boeing test panels radiographs all clearly illustrate the programmed defects. Initially our program used Eastman Kodak AA and RB film with a one mil Gd foil. These films are still used for preliminary exposures only; the bulk of the radiographs are now done on T and M film.

S. (Bob) Wang of Zenith-Rauland visited our facility recently. A test set-up mating the real-time imaging system with our 2 MeV prototype system gave very encouraging results. Resolution in the real-time mode was 32 line pairs per inch at a distance of 0.25 in., when a collimator L/D = 18, and neutron flux in the 10^5 n/cm^2-sec was used. He demonstrated via video tape resolution of 50 line pairs per inch when his system was used with a flux of 10^7/cm^2-sec.

Development of specific capabilities concerning applications of the systems to present industrial problems are underway. Inquiries concerning our capabilities or applications are welcome.

A neutron radiographic service at our facility has been offered which started March 15 of this year.

KAMAN NUCLEAR

1700 Garden of the Gods Road
Colorado Springs, Colorado 80907, USA
A. C. Berick, K. C. Price and D. E. Wood

Techniques for fast neutron radiography were developed for application to radiography of very thick objects for which thermal neutrons lack adequate penetrating power. Tests of various imaging techniques such as fluorescent screens, proton recoil radiators, and copper transfer led to the use of a radiator combined with fluorescent screens as the most satisfactory technique. A Kaman A-711 neutron generator was used to produce 14 MeV neutrons at outputs ranging from 4×10^{10} n/sec to 8×10^{10} n/sec. The beam diameter was about 2 cm. Since the source-to-film distance was 3 m to 5 m, the geometric resolution was reasonably good. However, in practice, the resolution was limited by the proton recoil range, which can easily be as much as 1 mm. Exposure times varied from 20 min to 30 hrs, depending on the thickness of the objects examined. Experiments with lead and polyethylene step wedges, as well as lead shields, indicated that a true fast neutron image had been produced. The film density for the step wedge images was roughly proportional to the fast neutron removal cross sections of the respective materials. Radiographs were taken of various electronic items, including potted components, hydrogenous materials inside of thick lead shields, and biological objects.

LOCKHEED-GEORGIA COMPANY

Lockheed Nuclear Products
P. O. Box 157
Dawsonville, Georgia 30534, USA
W. P. Walker

Lockheed-Georgia Company, at their Nuclear Products Plant at Dawsonville, Georgia, has added a Neutron Radiography Facility to the 3 MW (Th) Radiation Effects Reactor. After substantial development work, Lockheed is now offering this service to commercial and government users. This is a thermal neutron radiography facility with an exposure area of 14-inch by 17-inch. The gadolinium direct exposure neutron converter system is presently being used. The facility has a divergent beam collimator with an adjustable L/D ratio from 20 to 100 with a nominal thermal flux at the specimen of 2×10^6 n/cm^2-sec, having a cadmium ratio of 16 (Au), and a thermal flux (below cadmium cut-off) to gamma ratio of 8×10^5 n/cm^2-mr. A program to optimize the collimator with a substantial neutron flux increase is underway.

OREGON STATE UNIVERSITY

Radiation Center
Corvallis, Oregon 97331, USA
C. R. Porter

Neutron radiographic image quality from indirect conversion foils is being studied. The quality of the contribution from various depths in a Dy indirect conversion foil to the neutron radiographic image has been investigated. Images of a resolution test object (fine holes in a thin Gd foil) were produced using activated, 1 mil Dy transfer foils separated from the x-ray film by 0, 1, 2, 3, 4, and 5 mils of "cold" Dy absorber. Images thus formed were presented both with single and double emulsion type AA film. The images show a qualitative degradation in sharpness with increasing absorber thickness (contrary to some theories). The absorber technique does not, therefore, appear to offer an approach to higher resolution. Curves of Dy activity and film efficiency as a function of depth in the conversion foil and film density as a function of exposure have been prepared. These data were used to increase Dy activation for foils used with thicker absorbers so as to allow film exposure to be held constant for unbiased image quality determinations. These curves, along with the images from various depths, should provide the neutron radiographer, using Dy foils, with sufficient information to choose a proper balance between resolution and sensitivity for his particular application. The conclusions should also be applicable to other indirect foils such as In, Au and Ag.

PICATINNY ARSENAL

Dover, New Jersey 07801, USA
J. J. Hart

Picatinny Arsenal's neutron radiography project is being conducted under the U.S. Army Material Command's Materials Testing Technology program. Its purpose is to investigate neutron radiography for nondestructively testing munitions items and materials. The value and practicability of the method, as well as its limitations, in inspecting a broad range of materials and assemblies for a variety of possible defects will be experimentally tested, and critical comparisons will be made with conventional x-ray methods. Concurrently, the merits of various neutron sources will be tested and evaluated. The immediate objectives of the project are to conclusively identify those areas in the development of manufacture of munitions where neutron radiography can be of value, and to determine the equipment and techniques most likely to provide a practical, general purpose industrial neutron radiography system.

Negotiations are presently underway with the AEC to obtain a 5 milligram californium-252 source under their Market Evaluation Program for neutron radiography and other studies requiring high neutron fluxes. It is hoped that this source will be available about the middle of 1970, and it is intended that it be used to develop optimum designs for thermal neutron beam generation and neutron imaging, as well as to explore applications.

VIENNA, ATOMINSTITUT DER OSTERREICHISCHEN HOCHSCHULEN

Schuttelstrasse 115, A-1020 Wien, Austria
H. Rauch

Our neutron radiography facility (see Atomkernenergie 13 (1968) 444 and Neutron Radiography Newsletter 10 (1969) is now used in connection with the pulsed reactor operation to investigate the H-movement during fast running diffusion processes and chemical reactions in solids and liquids. A further project is the exact determination of the fuel burn-up.

****

#12. 1971

AEROTEST OPERATIONS

3455 Fosteria Way
San Ramon, California 94583, USA
R. L. Tomlinson

Aerotest Operations continues to offer courses in neutron radiography on a quarterly basis. Attendance is limited to six students for each class so that the students can have individual attention. As was the case in May, additional classes are scheduled if the regularly scheduled quarterly class is over-subscribed. Ten students successfully completed the course and passed the neutron radiographic interpretation test in May. The current emphasis of the course is directed toward qualification of non-destructive testing personnel who are presently trained in reading x-radiographs to interpret neutron radiographs. The three day course costs $150 for each student and includes a radiograph of parts supplied by the student.

Aerotest Operations has received approval from the Division of Licensing and Regulations of the AEC to expand its neutron radiographic capabilities. The new authorization allows Aerotest Operations to perform neutron radiography on Class A and B explosives in addition to the Class C explosives which have been routinely neutron radiographed since 1968. In addition, facility modifications include a capability to neutron radiograph components in excess of 40 feet in length.

A second independent neutron radiography facility has also been approved. The modifications will more than double Aerotest Operations' neutron radiographic production capacity. The two facilities will allow different resolution radiography to be performed at the same time.

The modifications include a new explosive handling facility which meets the latest government regulations and increases Aerotest Operation's storage capacity for explosives by a factor of ten.

ATOMICS INTERNATIONAL

P. O. Box 309
Canoga Park, California 91304, USA
O.R. Hillig, K. G. Golliher, V. A. Swanson and G. Gigas

Atomics International, Canoga Park, Calif. has completed the design and development of the L-85 water boiler reactor for neutron radiography. The reactor features both horizontal and vertical beams with variable neutron beam collimation and filters. The neutron beam strength for a resolution of L/D 100 is 10^7 n/cm^2-sec thermal with a gold/cadmium ratio of 5 to 1.

The L-85 uses an aqueous UO_2-SO_4 fuel enriched to >90 percent in U^{235}, and features a beryllium-graphite reflector.

BATTELLE - PACIFIC NORTHWEST LABORATORIES

Richland, Washington 99352, USA
K. L. Swinth

The neutron radiography performed at Battelle is done under sponsorship of the USAEC Division of Isotope Development. Our objective is to develop and investigate low-flux neutron radiography techniques and applications using ^{252}Cf. Previous efforts have led to the development of a portable shield and exposure facility for ^{252}Cf thermal neutron radiography (neutron camera). Evaluation of this shield has led to a new exposure facility. This unit uses the same shell; however, the bulk of the shielding and moderator is water which can be removed to facilitate positioning of the shield (70 lbs). After positioning, the shield is filled with water and the source transferred into the shield from a storage cask. This latter operation could be performed remotely to facilitate the handling of larger sources. Another experimental shield was developed to hold a larger (2 mgm) source. This shield has capabilities for remotely positioning the source at various positions in the shield and above the shield.

The use of europium foils for indirect neutron imaging has been developed for low-flux neutron radiography. Europium has a higher cross section, a higher natural abundance and a longer half-life than dysprosium, thus making it possible to obtain faint, but usable indirect images in a flux of 3 x 10^2 n/cm^{2}sec. High contrast images exhibit excellent resolution on both direct and indirect exposures. The problem encountered with europium metal foils is the extreme instability of the metal in air. After trying a number of techniques, we now handle the foils in an inert atmosphere and use a vacuum cassette during exposures. Results with such handling have been successful.

Direct imaging low-flux beams can be performed satisfactorily with standard techniques such as gadolinium foils; however, it is desirable to use the fastest techniques possible. Scintillating conversion screens show an enhancement in speed, but result in a loss of resolution. Gadolinium oxysulfide and fiber optic coupled ^{6}LiF-ZnS(Ag) have been investigated as means for enhancing resolution and sensitivity. The gadolinium oxysulfide screens have shown little improvement over gadolinium metal foils with regard to resolution, gamma discrimination or sensitivity. Using a fiber optics face plate with a ^{6}LiF-ZnS converter screen has yielded favorable results. For radiographs with comparable densities in the image area it took 50% more exposure (3.3 x 10^6 n/cm^2 vs. 2.2 x 10^6 n/cm^2) to produce the fiber optics image; however, the resolution improves probably due to smaller dispersion of light within the film and the scintillator.

A counter is being built for the "imaging" of neutrons. Previous counters for "imaging" neutrons have been built with gas fillings containing a neutron converter (^{10}B); however, the resolution of such counters is limited by the range of the alpha particles within the gas (0.6 cm). Our counter uses a neutron converter foil (^{6}LiF) with a collimator grid consisting of an electroformed mesh covering an imaging area of 3 in. by 4 in. The counter was purposely designed in such a manner that the gas pressure, degree of collimation, converter foil and the anode-cathode spacing could be varied to determine optimum operating parameters. Although the counter is still in the developmental stages; some evaluations have been performed. With a "thin" foil an unsharpness of 3.6 mm has been measured and with an improved collimator an unsharpness of 0.8 mm or better is expected.

UNIVERSITY OF CALIFORNIA AT BERKELEY

Department of Nuclear Engineering
Berkeley, California 94720, USA
S. N. Kaplan and K. Valentine

A radiography beam is being extracted from a 6-in radial beam port of the University reactor. In order to maximize the beam size we made the source point approximately in the center of the beam port. This gives a 12-in diam. spot at our object which is placed 3 ft. beyond the end of the beam port. We have a flux of about 5 x 10^6 n/cm^2-sec with an L/D of 200.

In collaboration with others we have performed preliminary measurements with a neutron-sensitive wire-grid proportional chamber.

UNIVERSITY OF BIRMINGHAM

Applied Nuclear Science Group
Department of Physics
Birmingham 15 2TT, U.K.
M. R. Hawkesworth and L. Holland

Since the last Newsletter the two long-standing n-radiography programs at Birmingham -- measurements of film-screen characteristics and flux distributions and intensities from various small sources in water -- have been concluded with the publication of reports on the response of Types 52 and 57 Polaroid film when used with NE 421 and 905 screens, and a Ph.D. thesis on the flux measurements. Work is continuing with efforts to relate unsharpness determinations, modulation transfer functions and the results of IQI tests to the accuracy of dimensioning objects through radiography. Particular emphasis is being placed on measurement of the swelling of irradiated reactor fuel from radiographs taken with non-reactor neutron sources.

The results of absolute measurements of the fluxes produced by D-D and D-T sources in water have recently been published. Reports on others parts of this study are being prepared for publication, but this will take time so we summarize below some of the observations of direct practical value. (1) water moderating ratios (source intensity ÷ peak thermal flux) for the various sources were found to be

Sb-Be (∿0.01 Ci)	45.5	± 5%
Am-Be (∿1Ci)	200	± 4%
D-D	196	± 9%
D-T	645	± 4%

^{124}Sb and ^{241}Am are significant thermal neutron absorbers so there is some dependence on source intensity.

A manganese bath system was used to calibrate the radioactive sources and the associated-particle technique for the accelerator sources. Gold foils calibrated in the GLEEP standard flux were used for the absolute flux determinations, and thin (∿0.2 mm) 1 cm diameter ^{6}LiF-ZnS scintillators on long Perspex (Lucite) light guides were used for the detailed distributions. (2) Increasing moderator size demonstrated that there is no improvement (<3%) in peak flux and useful beam intensity from any source for water spheres >20 cm in radius, though larger spheres are, of course, often needed to improve shielding. (3) Measurements on beams emitted from sealed airfilled perspex tubes, up to 10 cm in diameter, placed in the moderator showed in every case that maximum intensity is obtained when the tube base is in contact with the source -

the position of maximum thermal flux. Improvements in collimation obtained by lining the tubes with 1 mm of cadmium were assessed through the geometric unsharpness of "radiographs" of knife-edges. It was observed that increasing the source-object distance, though not always convenient, is an equally effective method of improving spatial resolution, there being similar exposure time penalties in each case. When the tubes were sleeved within 18 cm of the source, the maximum flux was noticeably (∿3% at 18 cm) depressed. (4) The effect of multiple beam tubes was studied by adding tubes one by one until there were five, all ∿8 cm diameter, mutually at right angles round the Am-Be source. The tube bases were coned just sufficiently to give each tube access to the peak flux. It was found that the current at a typical position for radiography fell by roughly 7.5% for each tube added, thus with five tubes the intensity from each was some 30% lower than that available when only one was in use.

The flux and beam studies were rounded off with a survey of all the particle accelerator neutron sources currently available, which has recently been extended into a short paper on the economics of neutron production reproduced later in this Newsletter.

BHABHA ATOMIC RESEARCH CENTRE

Trombay, Bombay 85, India
Y. D. Danoe, N. C. Jain, R. S. Udyawar

Work in the field of neutron radiography was started in April 1970. Preliminary investigation was carried out first at the thermal column of the 40 MW CIRUS reactor and then at the 400 KW swimming pool type reactor APSARA. The thermal neutron flux at the latter site was 5×10^5 n/cm^2-sec with a 76 cm x 8 cm x 8 cm parallel beam collimator. The gamma radiation level was 4 R/h and the picture was 8 cm x 8 cm.

Using gadolinium and indium foils, for direct and transfer techniques, initial parameters such as optimum foil thickness, exposure times and beam profiles were determined. Resolution better than 0.005" has been achieved with a cadmium test piece. Satisfactory radiographs of various objects like natural uranium cylinders, uranium oxide pellets, bakellite terminal strips, and film-batch holders have been obtained.

Development of B^{10} and Li^7 loaded scintillator screens for a neutron radiographic camera is now underway. A natural boron-ZnS plastic screen made here has shown promising results. The optimum thickness was 0.030" and the exposure time 3 min for an optical density of 1.5 on Ilford Cx film. Resolution is better than 0.005". A dry mixture of $^6LiCO_3$ and ZnS bonded with a plastic binder has also shown good speed and resolution. For a 0.030" screen, the exposure time was only 30 sec.

Development of a neutron radiographic camera using polaroid films is envisaged. We are also trying to apply this technique to metallographic studies, hydride formation, adhesive bonding etc. We plan to set up a mobile radiographic unit for general inspection and a neutron radiographic facility for fuel-pin examination.

CHALK RIVER NUCLEAR LABORATORIES

Chalk River, Ontario, Canada
Q. A. Walker

The neutron radiography unit at Chalk River was designed to radiograph active nuclear fuel elements at progressive stages throughout their life.

The source of neutrons for this facility is the NRX 40 MW heavy water moderated reactor with a thernal neutron flux at the vessel wall of 1×10^{13} n/cm^2-sec. The collimator is a small aperture divergent type in the form of an aluminum tube in which the diameter expands in steps from 1 1/2" at the aperture to 8 1/2" at the object end. It is lined with .032" cadmium sheet and is normally fitted with a changeable aperture plug which is currently 3/4" diameter. The collimator penetrates the graphite thermal column of the reactor to within 3 ft of the reactor tank wall. This space contains 30" of graphite which has the advantages of improving the cadmium ratio of the neutrons, reduces the gamma field and makes it easier to work on the collimator during shutdown. However, it also reduces the neutron flux by ∿1/4 but for present purposes there is sufficient neutron current of 1×10^7 n/cm^2-sec. Until recently the collimator has been used without a complete cadmium lining, but the cadmium lining has now been completed with a significant improvement in sharpness.

Our experience with the equipment has been limited so far due to a lengthy shutdown to change the reactor vessel. Good neutron radiographs have been obtained for active fuel elements, but most of the work has been done on non-active subjects and on U_3Si fuel in particular. In an attempt to examine the effects of hydriding of zirconium to a beryllium filter was introduced to produce a cold (.005 eV) neutron beam. This technique is to be retried now that the stray neutrons have been eliminated.

DOUNREAY EXPERIMENTAL REACTOR ESTABLISHMENT

Thurso, Caithness, Scotland, U.K.
A. R. Spowart

Work is proceeding on the development of the sealed tube neutron generator facility. Flux scanning work to date indicates a peak 14 MeV neutron output of 8×10^{10} n/sec at 119 kV and 9 mA beam current. A divergent collimator, 36 in. long giving an output frame size of 24 in. x 6 in. is in use (input dimensions 4 x 1 in) giving a thermal neutron flux of 10^6 n/cm^2-sec at the detector. Transfer radiographs require exposure times of 20-30 mins with 0.005 in. thick dysprosium foils and medium speed X-ray film. Scintillator radiographs of the same density (∿2.0) are produced in ∿1 min using NEGOT glass scintillator. Beryllium as a moderator is being investigated and the U^{235}/U^{238} flux booster gives a useful gain in neutron output (50%) compared to an oil system. Test exposures on a variety of active fuel samples are being carried out.

WESTERN REGIONAL HOSPITAL BOARD

Department of Clinical Physics and Bio-Engineering 11
West Graham Street, Glasgow C. 4
Scotland, U.K.
R. C. Lawson

The Department is interested in all aspects of neutron physics relevant to the application of neutrons in medicine and biology. At present three neutron sources are available.: (1) a 100 mCi Americium-Beryllium polyenergetic source; (2) a 14 MeV, 10^8 n pulse^{-1} K-tube generator, Elliott Bros. (London) Ltd., (3) a 14 MeV, 10^{11} n sec^{-1} neutron therapy machine, utilizing a Q-tube generator, will be commissioned in the Glasgow Institute of Radiotherapeutics.

A substantial scientific and technical program is underway to obtain essential fundamental physical and radiobiological data. Much of our work is concerned with collimated neutron beams. We are interested in applying radiographic and auto-radiographic techniques to investigate the gamma and neutron flux distributions from the target and their variation along the length of the applications. Fast neutron radiography of the limbs of the body is also being considered. We should be pleased to hear from any neutron radiographers who have experience in this field.

CHALMERS UNIVERSITY OF TECHNOLOGY

Department of Reactor Physics,
Storgaten 41, Goteborg, Sweden
N. G. Sjostrand

As a complement to the reactor neutron radiography work at the AB Atomenergi laboratory in Studsvik, experiments have been performed at the Department of Reactor Physics, Chalmers University of Technology, Goteborg, Sweden. With a ^{241}Am-Be source (10^7 n/s) useful radiographs have been obtained using a NE 425 scintillator and exposure times of about 10 hrs.

CENTRE D'ETUDES NUCLEAIRES-GRENOBLE

Section d'Application Des Radio elements
38-Grenoble-Gare, France
L. Vu Hong

An accelerator that provides 14 MeV neutrons has been investigated as source for thermal neutron radiography. For each system of moderators used (light water or a combination of light water and heavy water) the position and the dimensions of the collimator were optimized. In the same time the thermal flux was increased by a factor of 2,5 by fission reactions inside blocks of natural uranium placed around the target of the accelerator. These results apply to an accelerator that provides 2.10^{11} n/4π.s, the thermal flux at the outlet of the collimator is about 3.10^4 n/cm^2.s and the n/γ ratio is 1,8 10^4n/cm^{2}mRAD (collimation ratio, 1:20). Radiographic results are obtained with Gd converter, ZnS ^{6}LiF scintillator and Dy activation detector. For gadolinium a method of fading to eliminate the γ background in the radiographic emulsion has been suggested.

UNIVERSITY OF TECHNOLOGY-HELSINKI

Department of Technical Physics
Otaniemi, Finland
H. Reijonen

We have built a neutron TV system similar to that constructed by A.R. Spowart at Dounraey. We are also building a vertical beam tube for neutron radiography in our TRIGA Mark II 250 Kw reactor. Also under construction is a transportable neutron radiography unit based on ^{239}Pu-Be (10^7 n/sec) and polyethelene moderator. Applications have included inpsection of brazed joints, distribution of lubricants in bearings and inspection of active fuel elements.

LEWIS RESEARCH CENTER - PLUMBROOK STATION

Sandusky, Ohio 44870, USA
L. A. Thaler

Considerable effort has been expended on neutron radiography at the NASA, 60 MW Plumbrook Reactor. Our work has been diversified but mainly concerned with fuel capsules. A method has been devised to measure lateral swelling of nuclear fuel pins into a heat transfer gap using neutron radiography. A paper on this subject is being prepared and the summary has been accepted for presentation at the ANS meeting in Miami in October.

Some very interesting radiographs have been obtained of vapor transport of UO_2 fuel. A rather striking application of epithermal neutron radiography is presented in these radiographs. This program is relatively new and we will be continuing to accumulate epithermal radiographs as the vapor transport effect is followed.

Radiographs have been obtained of various types of lithium filled heat pipes. An NASA report is in preparation concerning some of the effort expended in this direction. Our future interests are varied. We would like to compare indium transfer radiographs and dysprosium transfer radiographs. The shorter exposure time required by the dysprosium would be beneficial to us. We would like to obtain epithermal radiographs in a shorter exposure time with more contrast, and plan to do this by using other detectors such as manganese and possible tungsten.

LOCKHEED MISSILES AND SPACE CO.

Sunnyvale, California
R. D. Marshall

As a user of neutron radiography, we would encourage standards activities with the following statement:

There is a need for a basic neutron radiography standard to control the radiographic imaging system variables. This would provide a basic general reference for all facilities. Unique requirements or procedures could then be detailed in individual organization specifications that would expand upon the basic standard.

UNIVERSITY OF MICHIGAN

Phoenix Memorial Laboratory
Ann Arbor, Michigan, USA
M. J. Flynn

Two general areas of medical applications of neutron radiography have been examined: (a) neutron radiography of thin pathology specimens, and (b) neutron radiographic detection of high cross section isotopes in biologic material. While the results may be of general interest in documenting the image characteristics of interest, no definite clinical applications have been justified. Results of these studies were published in the ANS topical conference on Neutron Sources and Applications (CONF-710402) and are available as unpublished reports from the above address. Current research activities involved with the neutron radiography facility at the University of Michigan's Phoenix Memorial Laboratory includes research on high resolution techniques, analytic descriptions of resolution and contrast in neutron radiographic systems, resolution measurement techniques along with a continuing interest in medical applications and a recent program to explore and document new industrial applications of neutron radiography (unpublished report available).

CENTRO INFORMAZIONI STUDI ESPERIENZE

C. P. 3986, Milano 20100, Italy
M. Mangialajo

At CISE Laboratories we started an experimental activity on neutron radiography in January 1971. We are particularly interested in checking out the uniformity in the composition of semiconductor alloys like $Cd_x Hg_{1-x}Te$. Qualitative results are now available and sample results will be exhibited in the transparency display at Miami, USA.

REED COLLEGE

Department of Physics
Portland, Oregon 97202, USA
W. L. Parker and J. A. Rau

For the past year at Reed College, under a contract from the Army Medical Research and Development Command to study the dental and medical applications of thermal neutron radiography, we have radiographed a large number of normal and tumor bearing tissue and bone specimens. Some of the results were interesting, but we are not quite ready to put the X-ray people out of business.

Concurrently we have been making a study of antiscatter grid effectiveness by measuring the photographic contrast obtained in the image of a special test object. Also we have made a theoretical study of the possibilities of micro-neutron radiography. Both of these studies will be reported at the fall conference of ANS.

UNIVERSITY OF TOLEDO

Toledo, Ohio, USA
J. A. Morley

An active study of the track-etch neutron radiography technique has been under way at the Plum Brook Reactor since August 1970. Both depleted and enriched uranium foils have been used with several types of plastics, including the new French Kodak LR-115 colored plastic, to produce high quality track-etch neutron radiographs.

Recent investigations into the enhancement of these radiographs have resulted in the discovery of a very simple enhancement technique. This technique involves placing a track-etch radiograph between two light polarizing filters, and viewing them with a diffuse transmitted light source. The filter-radiograph-filter package is then placed in a photographic enlarger. Light from the enlarger passes through the first filter (the polarizer) where it becomes polarized. This polarized light then passes through the track-etch radiograph and on to the second polarizing filter (the analyzer). If the light from the polarizer passes through an untraced portion of the radiograph, it will be blocked by the action of the analyzer. If the light from the polarizer passes through a track in the radiograph it will be scattered. This scattering process will change the polarization of the incident light, and because of this a portion of this light will be transmitted by the analyzer filter. This transmitted light is then passed through the enlarger optics for recording on photographic paper or film.

By passing only that light that has been scattered from the tracks in the radiograph the result is an increase in the signal (track) to noise (background) ratio. This method has been found to be most efficient when a diffuse rather than a collimated light source is used. The reason for this is just that randomly directed light will have a greater probability of being scattered by the randomly oriented tracks of the radiograph. The same results are obtained using the diffuse light of an ordinary X-ray viewing box.

The typical maximum density spread for a track-etch radiograph is about 0.22 optical density units. After being enhanced by the polarized technique the typical maximum density spread is in the order of 2.5 optical density units.

Efforts to improve track etch radiographs using polaroids and other enhancement techniques are being continued at the Plum Brook Reactor Facility.

ATOMININSTITUT DER OSTERREICHISCHEN HOCHSCHULEN

A-1020 Vienna, Austria
H. Rauch, N. Skiadopulos

Observation of the diffusion process in liquid and solid H_2 and D_2 by neutron radiography: The same experimental setup (Atomkernenergie 13 (1968) 444) is used for the neutron radiographic measurement of the H and D diffusion in H_2 and D_2 and for the observation of the ortho-para conversion in these substances at low temperatures. Conclusions concerning the molecular and jump diffusion can be drawn. For the measurements of rapid diffusion processes the pulsed operation of the TRIGA reactor is used.

WASHINGTON STATE UNIVERSITY

College of Engineering
Pullman, Washington 99163, USA
R. V. Subramanian

Our current work on neutron radiography is as part of a federal sponsored research project (Bureau of Mines) on the application of polymers to reinforce mine structures by injection into rock fissures, and is carried out at the Materials Chemistry Section of the Engineering Research Div., WSU. Neutron radiography is sought to be applied to determine the extent of penetration of polymer into the cracks of rock specimens in order to evaluate the applicability and efficiency of polymers in rock reinforcement. The neutron source is a TRIGA 1MW pool reactor. Using a divergent paraffin collimator, the neutron flux at the imaging area (port hole about 7" diameter) is 10^7 n/cm^2-sec. Work has been initiated on the determination of optimum radiographic conditions for test objects of polymer impregnated rock specimens. After successful laboratory tests, field work in mine areas using portable neutron radiographic equipment is also scheduled.

ARMY MATERIALS AND MECHANICS RESEARCH CENTER

Watertown, Massachusetts 02172, USA
J. J. Antal

The Materials Sciences Division of the Army Materials and Mechanics Research Center in Watertown, Mass. has just received its 5 mg Californium-252 neutron source from Savannah River under the AEC's Market Evaluation Program.

The experimental work area will be a 6-ft. diameter stainless steel tank filled with water having four horizontal beam ports reminiscent of a miniature research reactor. The Californium shipping container was designed to connect to the tank to serve as a storage place for the source while changes in experiments are made in the tank.

Neutron radiography of fibrous and laminar lightweight composite materials is planned. The major problems we anticipate are: obtaining the necessary high resolution image while accepting the consequent lowered intensity, and obtaining a sufficient subthermal neutron flux to allow exploitation of diffraction phenomena with filtered or velocity-selected neutrons. Several schemes for low temperature moderation at the neutron source will be tried to increase the subthermal flux. Previous work with such moderators at our nuclear reactor suggests that the small physical size of the californium source should be a distinct advantage in obtaining efficient moderation of neutrons to low energies.

WITTENBERG UNIVERSITY

Department of Physics
Springfield, Ohio 45501, USA
R. W. Beyer, C. M. Donges

Neutron radiography was performed at Wittenberg University using a 400 keV Cockroft-Walton electrostatic Accelerator from Accelerators Incorporated.

Materials used for direct exposure included: (1) 0.020 inch cadmium front and back screens, (2) 0.005, 0.125, and 0.250 inch PVT (polyvinytoluene) sheet scintillator NE-102 (A), (3) fast neutron detector NE-451 with ZnS(Ag) light cones, and (4) reworked polaroid cameras with 0.125 inch PVT scintillator. Indium foils 0.020 inch thick were used exclusively for transfer exposures. Kodak Medical X-ray Film (one side emulsion coated) was used for indium transfer and scintillation exposures, Polaroid Type 47 (3000 speed) Land Roll Film for reworked scintillatism cameras, and Kodak Medical Non-Screen X-ray Film two sides emulsion coated for other direct and transfer exposures.

The $D(d,n)\ He^3$ reaction was run at 200-300 keV with a 700 uA beam current, and yielded 10^7-10^8 neutrons/sec. Fast neutron radiographs produced by direct exposures were very poorly resolved. Thermal neutron radiographs were produced using a 1.50 inch piece of sheet paraffin, a cadmium-paraffin eggcrate collimator moderator, and a paraffin cavity of 1.25 inch thickness.

The $T(d,n)He^4$ reaction was run at 150 keV and 40 uA of beam current, and yielded 10^9-10^{10} neutrons/sec. The tritium target was centrally located in a 55 gallon oil drum filled with paraffin. Additional 3 inch thick paraffin moderator plugs were molded to fit a centrally located 5.50 inch inner diameter aluminum tube in the oil drum. Fast neutron radiographs produced with this setup were very foggy, but excellent thermal neutron radiographs were produced. A maximum thermal neutron flux was determined by indium activation analysis with approximately 2 inches of paraffin. Running without a paraffin plug in the moderating drum, an excellent radiograph was produced for an indium transfer exposure. Indium activity of approximately 20 mR per hour was sufficient for production of a good thermal neutron radiograph.

WORCESTER POLYTECHNIC INSTITUTE

Worcester, Massachusetts 01609, USA
Prof. L. C. Wilbur

We have completed our first MS thesis in the area of neutron radiography. The research dealt with the measurement and optimization of a number of parameters of the WPl neutron radiograph facility. The student, Lt. T. Lynch, an AEC Fellow, presented a paper on neutron radiography at the ANS Student Conference in Raleigh, N.C. this spring.

****

#14. 1976.

INSTITUTE J. STEFAN

Reactor Department
Jamova 39, 61001 Ljublijana, Yugoslavia
J. Rant

A neutron radiography program has been underway on the TRIGA Mark II reactor for four years. Projects include (1) inspection of TRIGA fuel elements. The work is continuing; (2) development of micro-neutron radiography techniques for metallurgical studies on thin samples

The work is continuing; (3) neutron induced alpha autoradiography to study boron behavior in metals; (4) measurements of edge spread functions for transfer method with Dy and In, and comparison with track etch imaging with Ca-80-15B material.

INSTITUTO D'APPLICAZIONI E IMPIANTI NUCEARI
Universita Di Palermo
90128 Palermo, Italy
Prof. C. Cappadona

At present in this field, we attend to neutron inspections of cylindrical surfaces using epithermal or cold neutrons. The device consists of a tube covered with a honeycomb envelope of cadmium having quadrangular cells that are filled with different materials according to the neutrons used. Cylindrical specimens are introduced into the annular void of this collimator and a cylindrical converter screen is fit within the annular void of the specimens. The remaining cavity is filled with suitable material in order to minimize interferences in the converter due to neutrons coming from opposite directions. This apparatus permits radiographs inside small reactors with transfer exposure method.

C.I.S.E. LABORATORIES
Milano, Italy
Dr. M. Mangialajo

This research laboratory is sponsored by the electric power generation utilities in Italy. A neutron radiography program has been underway here for several years. One special area of interest is the detection of metal hydriding in zirconium and other metals. For this, energy sensitive methods have been used. Dr. Mangialajo was present at the last two major neutron radiography meetings at Birmingham, U.K. and at Washington, D.C., USA, from which discussions this brief note was made.

CENTRO EURATOM DI ISPRA
Varese, Italy
R. Matfield

A neutron radiography facility is being designed and constructed using a vertical system on the ESSOR reactor. Collimator ratio will be 350:1, and the flux at the exposure position will be 10^8 n/cm^2-sec. The purpose is to neutron radiograph both active and nonactive samples using direct and indirect imaging techniques with photographic film and also cellulose acetate track imaging. Particular interest exists in safety evaluation and performance evaluation of water reactor fuel pins (defective fuel, power cycling, loss of coolant, etc.). Dummy fuel pins with controlled discontinuities have been prepared.

ATOMIC ENERGY BOARD
Pelindaba, Pretoria, South Africa
A. S. M. de Jesus

A neutron radiography facility is being designed and installed on the SAFARI I reactor (20 MW). This will be an out-of-pile, horizontal facility with initial capability for neutron radiography of non-radioactive objects, and with a later capability for radioactive objects by addition of external shielding. Collimator ratios selected are 150:1, 300:1, and 500:1. The thermal neutron flux at the input end of the collimator is 2.5 x 10^{13} n/cm^2-sec. The collimator incorporates a water cooled single crystal bismuth filter, 7.5 cm diameter and 15 cm long to reduce the gamma content of the beam.

A. B. ATOMENERGIE
Studsvik, Sweden

A neutron radiography program is underway at A.B. Atomenergi, Studsvik, Sweden. Some of the applications for this are discussed in a paper by H. Mogard, "A Quality Assurance Test of Safe and Reliable Operation of LWR Fuel." For the quality assurance program of light water reactor fuel, and also for fuel development), short term, high flux testing (as in the Studsvik 50 MW R2 reactor) is recommended over long term power reactor testing to reveal major quality deficiencies such as excessive fuel densification, presence of hydrogen in impurities, and inadequate resistance to stress corrosion clad cracking. Neutron radiography and metrology are listed as the two main tools used for nondestructive examination.

BUNDANG REACTOR CENTER

Indonesia
A. Kusnowo

A neutron radiography program is underway at the National Atomic Energy Agency, Bandung Reactor Centre. The work is performed by Mrs. A. Kusnowo (group leader), Mr. Kasan, Mr. Linggoatmojo and Mr. Suyadi. Their main neutron source is a Mark II TRIGA reactor. Early interest has centered on design of collimators and evaluation of activation transfer method imaging.

JAPAN

People active in neutron radiography programs in Japan include the following:

Kakuzo Tomii - (Chief of Nuclear Safety Research Reactor, Japan Atomic Energy Research Institute, Tokai-Mura, Naka-Gun Ibaraki-Ken). He has been involved in neutron radiography programs since 1968, with the JRR-4 2 MW pool reactor. Applications include nuclear and other fields. Technique studies have concentrated on imaging methods. The Nuclear Safety Research Reactor is an Annular Core Pulsed Reactor (TRIGA) newly installed this year. Neutron radiography will be one of its important facilities.

Noboro Sturuno - (Hot Cell Laboratories, Division of Research, Reactor Operation, Tokai Research Institute). He has been involved with neutron radiography programs at the JRR-3 reactor (D_2O moderated research reactor used for irradiated fuel evaluation).

Genichi Mastumoto - (Professor, Department of Nuclear Engineering, Nagoya University, Nagoya). He is interested in neutron radiography with accelerator sources, and also works with the JRR-4 reactor for these studies.

Masatoshi Kobayashi - (Deputy Head of Radioisotope and Nuclear Engineering School, Japanese Atomic Energy Research Institute). He has a long association with NR, and presented a paper on the subject at the Annual Meeting on Radioisotopes in Physical Sciences and Industry.

Yukinori Katsurayama - (Professor, Department of Nuclear Engineering, Kyoto University, Kyoto). This university recently hosted a technical group meeting on neutron radiography.

Toshiaki, Nojiri - (Kanagawa Industrial Institute, Kanagawa-Ken). One of his particular interests is the application of accelerators to neutron radiography.

Eiji Hiroaka - (Osaka-Fu Radiation Central Institute, Osaka). He is using a Van-De-Graaff accelerator for neutron radiography.

Shigenasa Enomoto - (Radioisotope Center, Oarai-Machi, Ibaraki-Ken). He is working on neutron radiography with a Cf-252 source.

Facilities in France

Introduction

This account is based on visits made by the author, J. P. Barton, to six neutron radiography groups in France during the summer of 1975. Responsibility for omissions or misrepresentations must be solely that of the author.

The overall position in France appears to be that neutron radiography is becoming solidly established, and its application is growing steadily. Effectively all of the research reactors in France have neutron radiography facilities, and all these facilities are in regular use.

By taking advantage of the very high fluxes available from many of these reactors, extremely high grade radiography is being performed. The three most recent facilities include two special 'MIRENE' reactors, installed for neutron radiography in fuel inspection hot cell facilities, and an automated facility installed adjacent to the below ground ISIS reactor for screening of full length light water reactor fuel pins. In addition to applications within the reactor development program, diverse industrial applications are accommodated, chiefly at the TRITON reactor, and this activity is steadily increasing in utility. Some details are presented below.

CENTRE D'ETUDES NUCLEAIRES
Cadarache

Contacts: J. Blaud, Safety Experiments Division, and M. Mercier, Head, Irradiated Fuel Examination Section.

Reactors that have been equipped for neutron radiography are PEGASE (50 MW), PEGGY (Low power), and SCARABEE (10 MW). Test capsules, such as simulated loss of coolant flow on nuclear fuel, are irradiated in SCARABEE and then neutron radiographed using this same source reactor. The neutron radiography position is outside the reactor shield, in contrast to many of the other fuel neutron radiography facilities in France which are under water. The CABRI reactor, used for power transient studies, is being modified and reconstructed. A hodoscope is being designed for use in this.

In addition to the neutron radiography facilities at Cadarache which have been installed on "existing" reactors, a special small 'MIRENE' reactor has been installed there for neutron radiography use in the hot cells. This is the second of a series of three reactors of the pulsed solution type built in France. The first was at the Valduc center, the third is installed for neutron radiography applications near the PHENIX fast breeder reactor at Marcoule. Cost of such neutron radiography reactors is about $300,000. The MIRENE facility at Cadarache is frequently used with a collimator ratio of 30:1 and with imaging by indium transfer to film equivalent to U.S.A. Kodak Type M.

CENTRE D'ETUDES NUCLEAIRES
Fontenay-aux-Roses

Contacts: M. Laporte, Engineer responsible for neutron radiography, M. Franzetti, Head, TRITON Utilization Section.

The reactor TRITON (7 MW) has two beam facilities in routine use for neutron radiography; one under water for examination of irradiated objects; the other a dry beam for general industrial applications. Track etch imaging is sometimes used instead of gadolinium conversion on the dry beam. The applications are diverse and total about $100,000 per year at an average of $20 per radiograph. The demand is increasing steadily at about 20% per year. Future possibilities include installation of a third beam (also dry), and installation of a cold neutron beam as cryogenic equipment is already installed for specially cooled irradiation experiments.

CENTRE D'ETUDES NUCLEAIRES
Grenoble

Contacts: J. P. Perves and J. Blin, Reactor Section, G. Breynat and M. Gilloppe, Accelerators Section; R. Cornuet, Head, Section for Applications of Radiation.

The three reactors at this center, SILOE (35 MW), MELUSINE (8 MW) and SILLOETTE (low power) all have operating neutron radiography facilities. The two on the former (high flux) reactors are both under water and are in regular use for inspection of irradiated samples. The SILLOETTE facility is a dry beam available for general applications but is not in large demand because of its comparatively low neutron flux.

The accelerator group does not have an active NR development program now.

One area of possible future interest for the accelerator group is that of liquid hydrogen cooled neutron beams since they have available considerable experience in cryogenic techniques.

LAUE-LANGEVIN INSTITUT
Grenoble

Contact: M. Ageron, Chief of the Cold Neutron Projects.

This is the center of the international very high flux reactor (57 MW in a very compact, under moderated, single annular element core). The reactor is not used for neutron radiography but is of interest to neutron radiographers because of the various neutron physics experience there (e.g., hot source and cold source). After extensive studies on cold source options, the center chose a large volume (50 liter) liquid deuterium source for installation adjacent to the core. Cost of this cold source was over $2 million. Guide tubes up to 50 m long gently curved on a radius of about 2 km are used in preference to filters for extraction of the cold neutron beams.

CENTRE D'ETUDE NUCLEAIRES
Saclay

Contacts: R. Barbalat, G. Farny, OSIRIS Reactor Section

The reactor OSIRIS (75 MW) and ISIS (800 KW) both have underwater neutron radiography facilities in routine use for examination of irradiated objects. Collimators of this type with the rubber seal or ice seal option can be manufactured and supplied at about $50,000. Four have been made so far.

In addition to the two underwater beams, a new facility has now become operational using a 'dry' horizontal beam extracted into a pit exacavated beside the below ground ISIS reactor. This is designed for routine neutron radiography screening of full length power reactor fuel pins. The pins are introduced in racks of five from a 14 ton transfer flask. System throughput capacity is 2000 pins per year assuming a four meter length to radiograph and use of a collimator ratio of 150:1 (3×10^{12} n/cm^2-sec at collimator input).

The imaging method that has been extensively refined and optimized at Saclay uses the track etch principle. Strips of type CA-8015 cellulose nitrate are supplied by Kodak-Pathe to match the full fuel length. Front and back converter screens of electroplated boron carbide (B-10 enriched) are used, and the exposure given is 3×10^9 n/cm^2. Advantages of the process include high radiographic quality, gamma insensitivity, ease of automation, and the ability to examine different levels of development for a single neutron exposure.

APPLIED ELECTRONICS LABORATORY
Paris

Contact: Dr. V. Chalmeton

This center was visited by colleague R. H. Bossi in the summer of 1975. They are working to develop microchannel plate electron amplifiers for neutron radiography. In a typical early device, the bunched fibers are formed into a 15 cm diameter plate containing 5×10^7 microchannels of 5 mm length and 10 μm diameter. The input screen is gadolinium, and the electrons, after amplification as they pass down the microchannels, fall on a p-11 phosphor output screen. Papers on this program have been authored by Dr. Chalmeton and published.

KODAK PATHE
Paris

This center has devoted considerable effort over several years to the development of track etch materials for neutron radiography under the leadership of Monsieur Barbier. Monsieur Barbier has recently retired from Kodak and the contact there on this subject is now Monsieur Fontini.

Facilities in U.K.

Introduction

This survey is based on visits made during the summer of 1975 by the author, J. P. Barton. Responsibility for errors and omissions is that of the author, not of the contacts listed.

An overall impression of the NR activity in the U.K. (as compared with the NR programs in the USA and France) is one of comparative under-exploitation for application work, but diversity in research work.

One of the U.K. centers (Aldermaston) has perhaps the most diversified potential for reactor based neutron radiographic technique development, and it is interesting to note that there is an increasing quantity of industrial application work being performed there, much of it on the special cold neutron facility.

Another of the centers (Harwell) has undertaken an extensive variety of technique development studies for fuel capsule inspection problems, but the center is at present to some extent limited by the lack of epithermal neutrons in the available spectrum.

A feature of the U.K. program is the relatively large proportion of accelerator based programs (Birmingham, Dounreay, and Woolwich, and Hammersmith Hospital), though it is not evident to this observer that sufficiently high quality performance can yet be obtained from these low intensity sources.

ATOMIC WEAPONS RESEARCH ESTABLISHMENT
Aldermaston

Contacts: G. Tuckey, J. Reichelt, M. Mullender.

Two reactors are used for neutron radiography at Aldermaston, The first is the steady state 5 MW HERALD pool reactor which has two beams devoted solely to neutron radiography: (1) a thermal neutron beam emerging from the thermal column, and (2) an epithermal beam that penetrates to look at the fuel region of the core. In addition, several other beams are used for neutron radiography on a shared basis including (3) a resonance energy monochromater beam (using a large aluminum crystal to diffract the selected energy), and (4) a cold neutron beam that makes use of a regrigerated deuterium source in a tangential beam tube.

Much of the industrial application neutron radiography in the U.K. is performed now at Aldermaston (together with Harwell) and it is significant that the majority of this application work is now done with the cold neutron beam. Advantages over thermal neutron radiography are (1) much lower attenuation for steel and other metals, (2) lower scatter effect, and (3) higher contrast for hydrogen and many other elements in the details that need to be revealed. Fortunately, although the cold beam is "shared," its use does not interfere with the other experiments since this uses only a diffracted portion of the beam. The cold neutron beam flux for radiography is 10^6 n/cm^2-sec. The reactor is operated on a 24 hour schedule.

The second reactor that has been used for neutron radiography studies at Aldermaston is the fast burst reactor VIPER. This facility can produce a sharp pulse of 0.5 milliseconds full width at half maximum power, and with an integrated yield of 4 x 10^{17} fissions per pulse. Experiments in flash neutron radiography have been performed using a polythene source block to obtain thermal neutrons, and using dysprosium foil activation transfer neutron imaging.

UNIVERSITY OF BIRMINGHAM
Radiation Center

Contacts: M. R. Hawksworth, J. Walker (Director, Radiation Center)

The neutron radiography program of the Birmingham group has available a variety of neutron sources including (1) a Dynamatron, (2) various other accelerators including cyclotrons and Cockcroft-Walton machines, and (3) the reactor facilities at Aldermaston and Harwell. The emphasis of recent studies has been on neutron moderation and imaging techniques for non-reactor source facilities.

The Dynamatron cost about $250,000. At the time of the visit it was normally operated for neutron radiographic studies using the Be (PN) reaction with a proton beam current of 0.2 mA and a voltage of 3 MV. This provides a fast neutron yield of 2 x 10^{11} n/sec. Eventually, the machine should be capable of providing 2 mA at 4 MV and a neutron yield of 2 x 10^{12} n/sec. By means of a magnet system, the proton beam may be turned to be used alternately in different rooms for different applications. At the 2 x 10^{11} n/sec yield a typical exposure time for gadolinium foil direct imaging with Kodak AA type film was 3 hours using a collimator ratio of 50:1.

Topics of particular interest include a determination of the absolute efficiency of gadolinium conversion, and evaluation of other imaging methods including rare earth scintillators, electron channel plates,and track etch systems. Application studies include nuclear fuel central cavity measurements and hydrogen diffusion coefficient determination for paladium foils.

MINISTRY OF DEFENSE
Fort-Halstead

Contacts: R. Bracher, R. Halmshaw, C. Hunt

This group has available a 5.5 MeV LINAC at the Woolwich Arsenal that can be occasionally converted from X-ray work to neutron radiography. They also have used the reactor facilities at Aldermaston and Harwell.

Interest exists in acquiring a new in-house facility for neutron radiography, and present leaning is toward a system designed primarily for high voltage X-ray work that can be alternately used as a neutron source.

Interest also exists in flash fast neutron radiography techniques such as might be applicable using a plasma focus source with yield of 10^{11} n/pulse, focal diameter of 1 mm, and flash duration of 50 nanoseconds. Tests of imaging systems run on a steady state fast neutron generator confirm that images can be obtained with exposures of about 10^7 n/cm^2 when using TRIMAX ALPHA 8 speed intensifying screens and TRIMAX type XM film, the rare earth matched set for medical radiography produced by 3M-U.K. company.

ATOMIC ENERGY RESEARCH ESTABLISHMENT
Harwell

Contacts: V. Crocker (Head,Materials Physics Division), A. Hollis, M. Pricetoe (Research Reactor Division), R. Parish, P. Keer (Nondestructive Testing Center)

The neutron radiography facility on the 20 MW DIDO reactor uses a radial beam that looks at the D_2O below the lower fuel level. The radiation is therefore low in gamma and epithermal neutron content. A thermal flux of 10^8 n/cm^2-sec is obtained at the 150:1 collimator ratio. Both direct exposure (gadolinium-Ilford N7E50 film) and activation transfer (indium-Kodak industrex C film) are commonly used. Over 7000 radiographs have been taken to date.

Most applications on this facility, designed to take radioactive specimens up to 4 inches in diameter, have been concerned with the reactor development program. However, a new exposure area better suited to general industrial applications has been designed. A recent point of interest concerns inspection of large quantities of aircraft turbine blades where it was noted that detail visibility fluctuated significantly with atmospheric humidity, and that storage in constant high humidity was therefore advantageous.

ATOMIC ENERGY ESTABLISHMENT
Dounreay

Contacts: This center was not visited on this trip. Information is from phone communication with K. Swanson and correspondence from D. Shepherd.

Neutron radiography at this center is available in the hot cells. The source is a sealed tube D-T generator of typical yield 6 x 10^{10} n/sec. Collimator ratios of 20:1 have been used with a field of view of 17 x 6 inches. Dysprosium foil transfer method imaging to Ilford industrial B type film requires a one hour exposure.

For inspection of complete fast reactor assemblies the center relies on an X-ray approach using a 400 kV source to shine down aligned avenues and a lead wheel shutter system to protect the film from lengthy gamma exposure.

U.K.A.E.A.
Windscale

Contacts: Center not visited.

A neutron radiography facility has been under preparation at this sight. It uses as a source of neutrons the demonstration Advanced Gas Reactor. The facility will be close to the U.K.A.E.A. Windscale Laboratories and also the British Nuclear Fuels Laboratories.

ATOMIC ENERGY ESTABLISHMENT
Winfrith

Contacts: S. Cotterell (Head, Technology Branch), J. Halliday, C. Hunt (Dragon Reactor Projects), D. Jakeman (Fast Reactor Safety Experiments), P. Barr (Post-Irradiation Examination).

This center has varied interests in neutron radiography although there is no on-site facility. Past users have included inspection of fuel capsules at other European reactors. Future possible needs are associated with (1) the center's extensive hot cell facilities, (2) the center's role in fast reactor safety and (3) the DRAGON reactor fuel inspection for kernal distribution within a compact, density distribution within a multicoated kernal, and fissile to fertile ratio changes from one region of fuel to another.

RUTHERFORD LABORATORY

Contacts: P. Davidson (Instrumentation Division)

The project of particular interest at this laboratory is a digital neutron imaging device being developed primarily for neutron diffraction and neutron spectroscopy, but with possible neutron radiographic and neutron gaging applications. A typical device under development consists of a line of neutron sensitive lithium glass scintillator fibers connected by fiber optical coupling to a channel plate amplifier system and a memory system. The device should be capable of very high neutron detection efficiency, and a system providing one hundred detector points and one hundred gray levels should cost about $5,000.

OTHER CENTERS IN THE U.K.

Other centers in the U.K. that have been involved in neutron radiography development include the London University's Reactor Center, the Scottish University's Reactor Center, Hammersmith Hospital and the University of Aston. As their name implies, the first two centers have reactors based facilities. D.K. Bewley at Hammersmith Hospital has worked with a cyclotron source of fast neutrons for neutron therapy and radiography, while A. J. Cox and colleagues at Aston have worked primarily with isotopic source facilities.

Activities in NR at Trombay, India

N.C. Jain
Nuclear Physics Division
Trombay, Bombay 400 085

A neutron radiography facility has

been operated on the APSARA reactor at Trombay. Tests with the VISQI image quality indicator gave ten faults when using conventional film/dysprosium transfer imaging, and six faults when using track etch imaging. Reports prepared are as follows:

1. Neutron Radiography for Nuclear Problems by N. C. Jain, Y. D. Dande and R. S. Udyawar, Proc. Symp. Nucl. Phy. & Solid State Physics, 15, B, 501 (1972-73). This paper describes our facility details and use of polaroid camera for neutron beam alignment work.

2. Neutron Radiography for Fuel Inspection by N. C. Jain, Y. D. Dande and R. S. Udyawar, Proc. Symp. Nucl. Sci. & Eng., FM3, March 1973. This paper describes the inspection of uranium and plutonium fuel.

3. Neutron Radiography of Ordnance Store, Pyrotechnique Devices and Composite Materials by Y. D. Dande, N. C. Jain & R. S. Udawar, Proc. Symp., "isotopic applications in industry" March 1976. This paper deals with the inspection of phosphorous filled marker shell, electric detonator, explosive cord for rocket program and B_4C-Al sheet for neutron shielding.

4. Neutron Radiography with Track Etch Detector by N.C. Jain (deals with the radiography with CA80158 film).

5. Use of Indu X-ray Film in Neutron Radiography by N.C. Jain, Y.D. Dande & R.S. Udyawar BARC/I-182.

6. A Polaroid Camera for Neutron Radiography by J. D. Dande and N.C. Jain barc/1-193.

7. Slow Neutron Scintillators for Neutron Radiography by R.S. Udyawar, N. C. Jain & Y. D. Dande, BARC/649.

SECTION I -- INDEX

PART II

ABSTRACTS AND TECHNICAL REVIEWS

#1. 1964

NEUTRON RADIOGRAPHY - WHY AND HOW

H. V. Watts
ITT Research Institute
Chicago, Illinois, USA

The role of neutron radiography is changing from being a laboratory curiosity to a valuable nondestructive inspection technique complementary to X-radiography and gamma radiography. Why this should happen is reviewed by a discussion of the applicability of neutron radiography and is illustrated with examples of both neutron and X-radiographs of the same object. How to perform neutron radiography is reviewed in two parts; neutron imaging detectors, and neutron sources. Continuing improvements on neutron detectors and sources permit characterization of the field as practical today, routine tomorrow.

THE NEUTRON RADIOGRAPHY OF URANIUM AND LEAD

A. W. Schultz and W. Z. Leavitt
U. S. Army Materials Research Agency
Watertown, Massachusetts, USA

A detailed analysis of neutron radiography as applied to the nondestructive testing of uranium and lead is presented. Experimental results using a reactor neutron beam, indium foil and X-ray film in the transfer method are described and yielded a penetrameter sensitivity of 2-2T for 2 to 4 inches of uranium and 2 to 6 inches of lead. Other applications of neutron radiography are presented including the testing of adhesive bonds in both light and dense materials and locating O-rings in assemblies.

THE ESTABLISHMENT OF A NEUTRON RADIOGRAPHY PROGRAM AT THE LOS ALAMOS SCIENTIFIC LABORATORY

B. L. Blanks and R. A. Morris
Los Alamos Scientific Laboratory
Los Alamos, New Mexico, USA

The los Alamos Water Boiler Reactor, having a maximum power of 45 kilowatts, has been used as a neutron source for neutron radiography. Experiments with various foil-film combinations have verified some of the published results. A neutron beam collimation device has been developed to improve the image resolution obtainable with this system. The application of neutron radiography to the inspection of several reactor components has been evaluated.

BIOLOGICAL APPLICATION OF NEUTRON RADIOGRAPHY

H. L. Atkins
Brookhaven National Laboratory
Upton, Long Island, N.Y., USA

The application of neutron radiography to biology is possible because of the high hydrogen content of living materials and the use of high capture cross-section elements as contrast agents. Hydrogen-rich substances have low X-ray opzcity but possess a high scattering cross section for neutrons. The range of contrast agents is greater in neutron radiography than in X-radiography since absorption coefficients for neutrons vary over several orders of magnitude. Living materials have such a high hydrogen content that scattering constitutes a serious problem in specimens more than 2 cm thick. Two approaches to counter this effect are the use of a grid similar to roentgenographic grids and the use of epithermal neutrons and resonance detectors.

PHOTOGRAPHIC DETECTION OF FAST NEUTRONS: APPLICATION TO NEUTRON RADIOGRAPHY

E. Tochilin
U.S. Naval Radiological Defense Laboratory
San Francisco, California, USA

The response of photographic emulsions to fast neutrons has been studied by direct measurements at two neutron energies and by exposure to high-energy

charged particles. Dose response was significantly less for neutrons that for gamma rays and decreased with decreasing neutron energy. Increased neutron sensitivity was obtained using organic scintillators as intensifying screens in conjunction with film. Neutron radiographs at two different energies were taken with step wedges made of Al, Cu, Pb and plastic. Radiographs were taken behind 2, 4, 6 and 8 inches of lead. Loss of photographic resolution from gamma rays produced in the test sample and by thermal neutron interactions will be discussed.

RADIOGRAPHIC ASPECTS OF FAST NEUTRON DETECTION

D. Polansky and E. L. Criscuolo
U.S. Naval Ordnance Laboratory
Silver Spring, Maryland

A progress report on fast neutron radiography using the 14 MeV neutrons produced from the D-T reaction in a 400 kv positive ion accelerator is presented. Experiments have shown that Eastman Type F film used with Patterson Type D screens has given the fastest response so as to make exposure times reasonable. Data on half value layers and film contrast versus subject contrast are presented. Considerable improvement in neutron converters is required before neutron radiography can begin to be applied to industrial inspection problems.

#7. 1967

NEUTRON RADIOGRAPHY POTENTIAL FOR BIOMEDICAL APPLICATIONS

(STATE OF THE ART REVIEW)

J. P. Barton

INTRODUCTION

In recent months a number of research workers in different laboratories have independently made known their interest in the biological possibilities of neutron radiography, and have indicated their intention to set up research programs. During the two years or so before this, little or no activity has been evident in this field. This brief analysis of the present position has therefore been prepared in the hope that it may be of some use to these or other people starting in a new area.

FORESEEABLE ADVANTAGES

There are three main foreseeable types of advantages for using neutron radiography in biological research. In each case neutron radiography should be capable of providing information not obtainable by X-rays or by any other inspection method.

1) Bone/Soft Matter

Neutrons penetrate solid bone rather more easily than hydrogenous soft matter such as the interior soft marrow or other tissue. This is the exact opposite of X-radiography; the X-rays being rapidly absorbed by the high electron density in bone. It seems possible therefore that neutron radiography techniques may be used to study soft tissue substances shielded by bone. For example it is understood that there are many diseases of bone which take place inside the bone structure, and which are not susceptible to investigation using X-rays.

2) Contrast Agents

Using neutron radiography the flow and uptake of contrast agents may be studied. This is analogous to the loading of the stomach with barium for X-ray contrast, but opens up a new wealth of possibilities due to the variety of possible elements, and indeed separated isotopes of elements, which may be used in chosen molecular combinations and provide sufficient contrast.

3) Hydrogen Density

Neutron beam attenuation is particularly sensitive to the hydrogen content of the regions of an object. X-radiography cannot distinguish between regions of high and low hydrogen content, and therefore neutron radiography may have special importance here, as well as for seeing small voids in hydrogenous tissue. It has been pointed out (1) that cancer tissues have higher hydrogen content and it is hoped they may be revealed for research studies in this way.

4) Dosage

A fourth and far more remote area of possible application enters if the eventuality is considered of inspecting living animals with acceptable, minimized, tissue dose.

In certain carefully calculated situations it seems possible that information may be obtained using neutron radiography whilst delivering less harmful cell damage dosages than would be suffered under X-radiography. This of course, is particularly likely for studies through large thicknesses of bone (wrists, knuckles, ankles, knees), and where contrast agent techniques are being used. Three particular points may be noted.

a) Neutrons may be detected with extremely high efficiency and the signal easily amplified (e.g. a 0.1 eV neutron gives several million electron volts energy deposited locally when captured by boron or lithium).

b) Epithermal (e.g. indium resonance 1.4 eV) neutron beams may be better than thermal neutrons in this respect. This is because the tissue damage does not result from kinetic energy changes of slow or resonance energy neutrons, but results from the energy liberated when the neutron is finally captured at the end of its diffusion path.

c) Narrow beams of neutrons have a considerable advantage over narrow beams of X-rays, because for X-rays the dosage is concentrated close to the beam path, whereas for thin neutron beams the dosage is very spread out, and much of the gamma radiation after neutron capture (and even the neutrons themselves) will escape from thin objects.

This fourth possible advantage area of neutron radiography is, however, a very difficult and unexplored field. Much research work will have to be done before a reliable evaluation of the possibilities can be made. Applications of the first two types of advantage areas, in biological research where radiation damage is not a relevant factor, seem more obvious.

SOME FORESEEABLE LIMITATIONS

Neutron radiography will be particularly suitable for thin biological specimens. For fairly thick specimens (e.g. above 2 cm - but depends on many factors) the technique becomes increasingly difficult because of

a) the high attenuation coefficient of tissue,

b) the very large proportion of neutrons which are scattered rather than absorbed.

Penetration may be improved by using beams of epithermal neutrons. Attenuation coefficients for good geometry have been calculated:

	Tissue	Bone
Thermal neutrons	3.2 cm^{-1}	2.26 cm^{-1}
1.4 eV resonance energy neutrons	1.47 cm^{-1}	1.12 cm^{-1}

Of course, it may be argued that high attenuation should not be insurmountable provided tissue dose is of no consequence, and high beam intensity or long exposure times may be used. However this assumes no interference from scattered neutrons, fast neutrons and gamma rays. Fast neutron and gamma ray interferences may be very effectively overcome by use of the activation transfer technique, but due to the saturation effect there is a lower limit to the incident flux acceptable. For dysprosium foil and fast X-ray film this lower limit is about 5×10^3 n/cm^2-sec. For an incident collimated thermal beam of 10^8 n/cm^2-sec from a high flux reactor this means that an attenuation of 2×10^4 can be accepted (3 cm of tissue, 4.5 cm of bone) assuming still that the scattered neutron problem is entirely overcome.

The scattered neutron problem has been evaluated (ref. 2) and some solutions proposed;

a) Use of narrow beams.

b) Use of highly collimated beams and calculated separation between object and detector.

c) Use of grid collimators between object and detector.

d) Use of monoenergetic resonance energy neutron beams and resonance energy detectors and filters, thereby discriminating against neutrons having suffered an energy loss.

Some figures which enable the calculation of each of these four possible solutions are given in the references.

The use of fast neutrons (MeV region) would provide higher penetration, but there are obvious limitations:

a) Contrast between different elements is very small.

b) Detection methods are at present undeveloped.

c) There will be the difficulty of partially slowed neutrons mixed with the emergent beam.

d) Tissue damage per neutron signal will be high.

However, in the long run, fast neutron radiography (MeV region) intermediate energy neutron radiography (KeV range) (3) and other ideas such as the use of pulsed reactor beams may well prove valuable.

GENERAL CONCLUSION

Useful thicknesses of biological material may be examined using neutron radiography and the possibilities seem exciting. There should be encouragement for neutron physicists and biological experts to work together in exploring some of these avenues.

One particular improvement during the last year or two is the availability of very highly collimated very high intensity neutron radiography facilities, such as the one described in reference (4). This high product of collimation and intensity (one or two orders of magnitude superior to earlier facilities) should enable the scattered neutron problem to be more thoroughly overcome.

REFERENCES

1. Frigerio, N. A., Argonne National Laboratory (private communication, 1967).

2. Barton, J. P., Applied Materials Research, 4, 90, April, 1965 - Contrast Sensitivity in Neutron Radiography.

3. Burrill, E. A., High Voltage Engineering Corporation (private communication, 1967).

4. Barton, J. P., and Perves, J. P., British Journal of Nondestructive Testing, 8, 79, Dec. 1966 - Underwater Neutron Radiography Using a Conical Collimator.

APPENDIX I - PUBLICATIONS OF BIOLOGICAL POSSIBILITIES OF NEUTRON RADIOGRAPHY

Barton, J. P., Physics in Medicine and Biology, 9, 33, Jan. 1964.

Anderson, J., *et al.*, Brit. J. Radiol., 37, 937, Dec. 1964.

Barton, J. P., Physics in Medicine and Biology, 10, p. 209, April 1965.

Atkins, H. L., Materials Evaluation, 23, 453, Dec. 1965.

Tochilin, E., Physics in Medicine and Biology, 10, 877, Dec. 1965.

In addition an unpublished student report has been prepared by R. J. Hurrell, University of Birmingham, October 1964, entitled, "Tissue Dose Distributions for Radiographic Neutron Beams of 1.44 eV and area 0.25 cm^2 and 1 cm^2."

Other Reports of Possible Interest to People Starting in This Field

1. Frigerio, N. A., Phys. Med. Biol., 6, 541, 1962.

2. Melkonian, E., Phys. Rev., 76, 1760, 1949, Slow Neutron Velocity Specrometer of O_2N_2H, H_2, H_2O and Seven Hydrocarbons.

3. Brownell, G. L. and Sweet, W. H., Geneva Conf., p. 881, 1958, Studies in Neutron Capture Therapy."

4. Block, J. and Shon, F. J., Health Physics, 8, p. 533, 1962, Neutron Dose Measurements by an Attenuation Technique.

5. Snyder, W. S., Nucleonics, Feb. 1950, p. 146, Calculations for Maximum Permissible Exposure to Thermal Neutrons.

6. Frigerio, N. A. and Jordan, D. L., Biological Effects of Neutron and Proton Irradiation, Vol. 1, IAEA, Vienna, 1964, "Pattern of Lethality and Absorbed Dose Distributions in Mice for Monoenergetic Neutrons."

7. Fairchild, R. C., BNL 6824, Experimental Thermal and Epithermal Neutron Penetration in a Phantom Head.

8. Frigerio, N. A., (private communication) - A computer program has been prepared capable of studying tissue dosage and neutron history for specified neutron incident beam and tissue target conditions.

APPENDIX II - NAMES AND ADDRESSES OF PEOPLE HAVING RECENTLY EXPRESSED INTEREST IN WORKING IN THIS FIELD

Mr. Blaise
CEPEC Compagnie General De Telegraphie Sans Fil Domaine of Carbeville
B. P. No. 10
91 Orsay, France

Mr. Body and others
Scottish Universities Reactor Centre
Kilbride, Scotland

Dr. Mark Brown, M. D. and Dr. Paul Parks
Department of Radiology
Medical College of Georgia
August, Georgia 30902, U.S.A.

Professor Cherigie
Hospital Saint Antione
Service Electro-Radiologie
187 Rue du Faubourg
St. Antione, Paris 12°

Mr. C. Desandre
DPE/SPP
C.E.N., Grenoble, B.P.
No. 1, Saint Paul-Lez-Durance B-du RH
France

Mr. Farny
SPE ISIS-OSIRIS
C.E.N. Saclay
B.P. No. 2
Gif-Sur Yvette, France

Professor Kellershohn
Service Hospitalier Frederic Joliot
Hospital D'Orsay
S & O, France

Professor Lauac-Jeantet
Hospital Droussacs - La Charite
Service Electro-Radiologie 96
Rue Didot, Paris 14°

Mr. J. P. Perves
C.E.A.,
C.E.N., Grenoble, B.P. 260
Grenoble 38, France

Mr. C. R. Porter
Radiation Center
Oregon State University
Corvallis, Oregon 97331, U.S.A.

#8. 1968

NEUTRON RADIOGRAPHY USING NON-REACTOR SOURCES

(STATE OF THE ART REVIEW)

J. P. Barton

Progress has been made recently in evaluating small (non-reactor) neutron sources for neutron radiography. Several centers are now considering setting up such systems (about twenty groups have had discussions with this writer) (1) and many of these are for important application work. Examples of thermal neutron radiographs taken by means of non-reactor source techniques have been published in four papers during this decade (2, 3, 4, 5). Discussion of non-reactor source techniques in these papers has concentrated on one particular type of radioactive source (Sb-Be) (2, 5), or has been brief (3, 4). This present paper has the objective of helping to put the current position into perspective, and it is hoped that such an introduction will be of particular use to groups now considering embarking in this field.

INTRODUCTION

It was demonstrated as long ago as 1956 that useful quality neutron radiography could be performed using a nuclear reactor as the source of neutrons (6). Within the last few years the technique has been applied successfully to a variety of applications. All have used a nuclear reactor as the neutron source (7).

If neutron radiography could be performed with small neutron sources of comparable cost and convenience to standard X-ray generators, then the technique might, hopefully, become as widely useful as X-radiography is today.

A variety of neutron sources is now available comprising different types of neutron generators and radioactive sources. Doubtless even further advances will be made in the near future, both in generators (8) and in radioactive neutron sources (9).

EARLY WORK - SMALL SOURCE-THERMAL NEUTRON RADIOGRAPHY

Investigations into the possibilities of performing thermal neutron radiography using non-reactor neutron sources have been undertaken by a number of people. Kallman (10) and Peter (11) experimented with accelerator sources of outputs about 10^7 and 10^{11} neutrons/sec respectively. Their reports did not include details about the collimation achieved, or the quality of the neutron beam. Difficulties were reported due to the high proportion of interfering radiation (X-ray, γ-ray, fast neutrons, and partially slowed neutrons). Early experiments by Watts (12) using 1 curie of Pu-Be; Berger (13) using 0.5 curies of Ra-Be and a $Li^7(p,n)$ Van de Graaff; Barton (14) and Dunnicliffe (15) using a D-T and D-D accelerator and a 1 curie Po-Be source; and Rathmann (16) using a linear accelerator with beryllium target; all gave essentially regative results. In this early research work, neutron beams sufficiently well collimated to furnish genuine thermal neutron radiographs of realistic objects (thicker than 1 cm) were not obtained. All of the above mentioned authors stressed the effects of interfering radiation as being a serious limitation.

One author, Warman (2), did report enthusiastically about neutron radiography experiments using 1,000 curies of Sb-Be. However, for this particular source (a γ-n source), the gamma radiation is particularly intense and very penetrating. It was therefore necessary to use the gamma insensitive activation transfer photographic technique. This has a low efficiency, i.e., it wastes a large proportion of the available neutrons, and cannot integrate over long exposure times. The collimator was a cadmium tube of diameter 2 inches and length only 3 inches. Because of the high gamma yield a source powerful enough for transfer method radiography would not be easily portable. There may be, however, applications for which Sb-Be sources are suited, such as the particular task of radiography of highly radioactive objects where remote handling techniques and activation transfer photography are already necessitated.

FAST NEUTRON RADIOGRAPHY

Small sources appear particularly well suited for fast neutron radiography. The advantages here are that moderation and collimation are not required, and therefore much more efficient use of the available neutrons is possible. Criscuolo and Polansky reported some experiments on fast neutron radiography using a D-T neutron generator several years ago (17) and more recently other workers (18, 19, 20) have published reports. Some experiments on fast neutron radiography have also been undertaken by Barton at Birmingham using a D-T and D-D neutron generator, and by Berger at Argonne using an Am-Cm-Be source. These two workers have been unable to establish that their radiographs were true fast neutron radiographs rather than mixtures of partially slowed neutrons, X-rays and gamma rays.

Research into methods of fast neutron detection for radiography is now planned by at least two persons: H. Berger at Argonne and W. H. Wilkie at Georgia Institute of Technology. If fast neutron radiography does prove to be practical and to have important applications, one radioactive neutron source would seem to have particularly promising potential (21). This is Cf^{252}. For example, a 10^{10} n/sec radioactive source of another kind may have a diameter of 10 mm whereas a Cf^{252} source of only 10^8 n/sec might have a diameter of less than 1 mm and be capable of superior radiography performances in fast neutron point source geometry.

THERMAL NEUTRON RADIOGRAPHY - RECENT DEVELOPMENTS

Activation Transfer - Neutron Generators

The possibility of using a 10^{11} n/sec output neutron generator for activation transfer method thermal neutron radiography, suitable for highly radioactive objects, has been demonstrated (22). Dysprosium foil of thickness 100 μ was used with saturation exposures of a few hours, and in this case the collimation was limited to a ratio of 10 x 100.

Activation Transfer - Radioactive Sources

Cutforth at ANL Idaho (23) and Farny at Saclay (24) are experimenting with Sb-Be as the neutron source. Cutforth initially used about 400 curies of Sb, and has just installed 6,000 curies. Farny has worked with 10,000 curies Sb and is considering a source of 100,000 curies. Whether such sources will be practical and economical must depend on the particular situation (availability of Sb irradiation facilities, etc.).

Very recent experiments by Barton and Klozar at Argonne have demonstrated that activation transfer pictures of low density are possible using the 10^9 n/sec Am^{241}-Cm^{242}-Be source with a 10 x 100 cadmium collimator.

Direct Exposure - Neutron Generators

Thermal neutron radiographic characteristics have been evaluated for a range of collimator designs, experimenting with different arrangements (moderator, geometry, shielding and detector) for three different neutron generators (one small, of output 10^9 n/sec; two larger, of outputs 10^{10}-10^{11} n/sec (25). This evaluation does show that useful quality direct exposure thermal neutron radiography is practical using these generators. Collimations as high as 3 x 100 (input diameter x length), which is equivalent to that of the Juggernaut reactor beam for example (26), have been achieved. Several other workers have been investigating, or are planning to investigate, the use of neutron generators for direct exposure thermal neutron radiography (e.g., 1, 27-33) but as yet no reports have been distributed.

Direct Exposure - Radioactive Sources

The first known successful direct exposure neutron radiography using a radioactive source made use of Am^{241}-Be (34, 35), a neutron source which had only recently become available. Thermal neutron radiographic characteristics were proven using a 3 curie source (7 x 10^6 n/sec) for collimator ratios over the range 12 x 100 to 3 x 100 (Cf Juggernaut 3 x 100). This source has a low gamma emission which is an important advantage for direct exposure neutron radiography. The low gamma emission also enables the source to be made relatively portable. Americium-241 is a by-product of plutonium burnup in power reactors, and should become increasingly available in the future. A neutron radiography facility using 30 curies of Am^{241}-Be is now installed at Saclay (36).

The neutron output of an Am^{241}-Be source may be increased by a factor of about 100 by irradiation in a reactor neutron flux (37). The effective half life of the resulting Am^{241}-Cm^{242}-Be source is only 163 days and the original Am^{241}-Be (half life 470 years) is largely destroyed. However, in some circumstances there may be a definite demand for this high output over a short period. Some experiments to evaluate Am^{241}-Cm^{242}-Be for neutron radiography have been undertaken at Saclay (38) and also at Argonne (39). The experiments now underway at Argonne are using Am-Cm-Be sources of strengths 10^7 and 1.1 x 10^9 n/sec and moderators of BeO and H_2O. It has been demonstrated that good quality direct exposure neutron radiography is, in fact, possible using this type of source.

Although Am^{241}-Be and Am^{241}-Cm^{242}-Be are the only sources which, to our knowledge, have so far been demonstrated as capable of thermal neutron radiography, it seems probable that other sources such as Po^{210}-Be and Pu^{239}-Be would be suitable also. One particularly promising source which may become relatively inexpensive in the future is Cf^{252} (9). The first sizeable quantities of this will become available soon, and experiments will be undertaken at Argonne to evaluate the neutron radiography characteristics.

RESULTS AND CONCLUSIONS - THERMAL-DIRECT EXPOSURE

This summary refers exclusively to thermal neutron radiography of ordinary objects (i.e. not highly radioactive objects). It is possible to summarize here only very briefly, and only drawing on the experimental results and technical views of this particular author.

The potentiality of small source neutron radiography is seen to have two fundamental limitations:

a. Interfering radiation
b. Shortage of neutrons

Both problems increase as the degree of beam collimation is increased. The task is to optimize the various parameters in order to satisfy the particular requirements of a given application.

These variable parameters are:

a. Choice of source

b. Intensity of source

c. Choice and configuration of moderator

d. Beam extraction

e. Collimation system

f. Filter system

g. Shielding system

h. Detection system

The problems of the shortage of neutrons, which sets a statistical limit on the information transmitted, is considered (by this author) to be the more fundamental limitation. The approach has therefore been to make maximum use of those neutrons available, i.e.:

1. Use direct exposure techniques (thereby enabling long integration times to compensate for low neutron intensities).

2. Use the most efficient neutron converter system (a report on optimized scintillator converters is available (40), further work is underway).

3. Overcome the problem number 1 - interfering radiation - by manipulation of the other seven variables (a-g); not by a compromise on the choice of the most efficient detection system. (Reports on moderator systems (41, 42) are available). Other reports are in preparation.

Not all applications for neutron radiography will require the highest possible picture quality. Those that do will probably best be solved by use of a nuclear reactor neutron source. Moderate quality radiography can be achieved using small sources (Table 1), and, if long exposure times are acceptable (e.g. overnight exposure), very small inexpensive sources may be used. Such sources may be fairly portable and easy to manipulate.

The cost of a neutron source rises rapidly with the neutron yield, and it will be important to design the facility to suit the particular application and circumstances. For example, the geometric unsharpness, the inherent screen and film unsharpness, and the neutron statistical unsharpness should be carefully matched to each other, and to the inspection task requirements.

Table 1 outlines some of our experimental results. By reference to survey experiments such as this it should be possible to decide:

1. Whether small source techniques can satisfy the specified requirements of a particular application.

2. What will be the most suitable type of apparatus for the conditions of that particular application.

ACKNOWLEDGEMENTS

These studies of non-reactor source neutron radiography have been carried out with the kind cooperation of the following: University of Birmingham, Section of Applied Nuclear Science; U.K.A.E.A. Harwell and Aldermaston; Centre d'Etudes Nucleaires de Grenoble, Section d-Application des Radioelements and Service des Accelerateurs; Argonne National Laboratory, Metallurgy Division.

REFERENCES

1. J. P. Barton, "Interest in Neutron Radiography Using Accelerator Sources," DR/SAR G/67, December 1967 (unpublished report).

2. E. A. Warman, "Neutron Radiography in Field Use," Materials Evaluation, Vol. 23, 1965, p. 543.

3. J. P. Barton and J. L. Boutaine, "Premiers Developpements de la Radiographie Par Neutrons en France," Bulletin D'Information, A.T.E.N. Sup. No. 66, July-Aug., 1967, pp. 4-9.

4. J. P. Barton, "Toward Neutron Radiography of Radioactive Objectives in Hot Cells," Transactions American Nuclear Society, Vol. 10, No. 2, Nov. 1967, pp. 443.

Table 1

Source Strength Yield Fast Neutrons Per 4π Solid Angle	Sources Evaluated	Thermal Neutron Flux Collimator Input n/cm^2-sec	Typical Collimation Ratio. Input Diameter x Length	Beam Intensity at Collimator Output n/cm^2-sec	Typical Exposure	
10^7 n/sec	Am^{241}-Be	10^4	3 x 100	1	3 days	Scintillator + Fast Film
			10 x 100	10	9 hours	"
10^9 n/sec	Small Neutron Generator Sames B.S.1 Am^{241}-Cm^{242}-Be	10^6	3 x 100	10^2	1 hour	"
			10 x 100	10^3	6 mins	"
10^{11} n/sec	D-T Neutron Generator (Sames)	10^8	3 x 100	10^4	½ min	"
			10 x 100	10^5	2 mins	Scintillator + Fine Grain Film
	Reactor at 1 KW Juggernaut (Argonne)	10^9	3 x 100*	10^5	2 mins	"
	Reactor at 200 KW Juggernaut (Argonne)	2×10^{11}	3 x 100*	2×10^7	1 min	Direct Exposure Gadolinium Foil + Fine Grain Film (0.0005 In.) (Kodak Single R)
	High Quality Reactor Facility (Melusine 4 MW Siloe 15 MW Grenoble)	10^{13}	1 x 100	10^8	Sufficient Intensity and Collimation for Penetration Through Thick Object and Still Use Thin Activation Transfer Foils and Very Fine Grain Film	

*Note: The Juggernaut beam collimator is a simple parallel sided hole penetrating the reactor shield. It is not cadmium lined. All other collimators quoted were lined with a material opaque to thermal neutrons (Cd or B), and were of the divergent type.

5. D. C. Cutforth, "On Optimizing an Sb-Be Source for Neutron Radiographic Applications," Materials Evaluation, Vol. 26, No. 4, April, 1968, pp. 49-53.

6. J. Thewlis, "Neutron Radiography," British Journal of Applied Physics, Vol. 7, 1956, pp. 345-350.

7. Neutron Radiography Newsletters Nos. 1-7, published by the American Society of Nondestructive Testing, Evanston, Illinois.

8. "Accelerator Targets Designed for the Production of Neutrons," Euratom Proceedings, EUR 2641 d, f, e, Symposium, Grenoble, June 21-22, 1965.

9. N. L. Stetson, "Transplutonics - Promising Neutron Sources for Research," Nucleonics, Vol. 24, Nov. 1966, pp. 44.

10. H. Kallmann, "Neutron Radiography," Research, Vol. 1, 1947, pp. 254-260.

11. O. Peter, Naturforscher 1, 1946, p. 557.

12. H. V. Watts, "Research on Neutron Interactions in Matter as Related to Image Formation," ARF 1104-27, Aug. 1962 (unpublished report).

13. H. Berger, "Neutron Radiography: A Second Progress Report," ANL-6515, pp. 28-52, 1961.

14. J. P. Barton, "Concepts in Neutron Radiography," University of Birmingham, 1963 (unpublished report).

15. C. J. Dunnicliffe, "Development of a Portable Neutron Source Suitable for Use in Radiography," University of Birmingham, Oct. 1964 (unpublished report.

16. D. W. Rathmann, "Preliminary Experiments in Neutron Radiography with a Radiographic Linear Accelerator," Thickol Chemical Corp., Aug. 1964 (unpublished report).

17. E. L. Criscuolo and D. Polansky, "Fast Neutron Radiography," Missiles and Rockets Symposium, U.S. Naval Ammunition Depot, Concord, California, April 18, 1961.

18. J. Anderson *et al.*, "Neutron Radiography in Man," Brit. J. Radiol., Vol. 37, Dec. 1964, p. 937.

19. E. Tochilin, "Photographic Detection of Fast Neutrons," Physics in Medicine and Biology, Vol. 10, Dec. 1965, p. 877.

20. D. E. Wood, "Fast Neutron Radiography with a Neutron Generator," Transactions American Nuclear Society, Vol. 10, No. 2, Nov. 1967, p. 443.

21. J. P. Barton, "Transplutonium Isotopic Neutron Sources - Foreseeable Future Demand for Neutron Radiography," April 1968 (unpublished report).

22. J. P. Barton, "On the Possibility of Using a D-T Neutron Generator for the Radiographic Inspection of Highly Radioactive Elements," SAR-G/66-370, Nov. 1966 (unpublished report).

23. D. C. Cutforth, "Neutron Radiography Newsletters," Nos. 1-7.

24. M. Farny, "Neutron Radiography Newsletter," No. 7, Nov. 1967, p. 3.

25. J. P. Barton, "Neutron Radiography Using Small Neutron Sources," Centre d'Etudes Nucleaires, Grenoble (unpublished - report in preparation).

26. H. Berger, "Characteristics of a Thermal Neutron Beam for Neutron Radiography," J. Applied Radiation and Isotopes, Vol. 15, 1964, pp. 407-414.

27. J. H. Hamilton, "Neutron Radiography Newsletter," No. 4, April 1966, p. 4.

28. L. Holland, University of Birmingham, private communication (1967).

29. G. Lachese, "Neutron Radiography Newsletter," No. 6, April 1967, p. 2.

30. S. Kawasaki, Tokyo Shibaura Electric Co., Kawasaki, Japan (private communication, 1967).

31. M. Radwan, Institute of Nuclear Research, Warsaw, Poland (private communication, 1968).

32. M. Mouraille, "Neutron Radiography Newsletter," No. 7, Nov. 1967, p. 3.

33. L. Vu Hong, C. E. N. Grenoble (private communication, 1967).

34. J. P. Barton and P. Corompt, "La Neutrographie Possibilities et Avenir" Symposium held at Saclay, 5 Oct. 1966 (unpublished reports).

35. J. P. Barton, "Neutron Radiography Newsletter," No. 6, April 1967, p. 3.

36. J. L. Boutaine, "Neutron Radiography Newsletter," No. 6, April 1967, p. 3.

37. D. C. Stewart et al., "The Production of Curium by Neutron Irradiation of Am^{241}," ANL-6933 (unpublished report).

38. J. L. Boutaine, C.E.N. Saclay, private communication, 1967.

39. J. P. Barton and M. Klozar, Argonne National Laboratory (unpublished work).

40. J. P. Barton, "Scintillators in Neutron Radiography," DR/SAR G/67-46, Dec. 1967 (unpublished report).

41. M. Mouraille, "Thermalisation de Neutrons Rapides Produits per un Accelerateur Electrostatique de Fabile Energie," ACC/67-06, July 1967 (unpublished report).

42. J. P. Barton, "Moderation of Neutrons from Point Sources - Application - Neutron Radiography," DR/SAR-G/67-45, Dec. 1967 (unpublished report).

43. J. P. Barton, "Divergent Beam Collimator for Neutron Radiography," Materials Evaluation, Vol. 25, No. 9, Sept. 1967, p. 45A.

THE SPECIFICATION OF RADIOGRAPHIC BEAMS IN NEUTRON RADIOGRAPHY

M. R. Hawkesworth
Applied Nuclear Science Section
Department of Physics
University of Birmingham, England

Looking through published work recently to compare "speed" and "contrast" performance with figures being measured in Birmingham, we were frustrated by the lack of detail presented regarding the characteristics of the beams used. The writer would like to suggest, therefore, that more information be given when the beam intensities and exposures found to be necessary for a particular application are published.

Usually only a figure (Φ) is quoted, labelled "beam intensity" or "flux," and this is sometimes accompanied by a figure for the "cadmium ratio." Φ is presumably $\int_0^\infty \Phi(E)\, dE$, or is it? The cadmium ratio indicates the fraction of neutrons in the beam with energies greater than ~ 0.4 ev, but without other information regarding the neutron energy spectrum it is of little relevance.

To measure a flux one always observes a reaction rate (R), in some detector, which is divided by an efficiency factor (ε) and an average cross-section ($\bar{\Sigma}$). When the energy spectrum of the beam is known $\Phi = R/\varepsilon \cdot \bar{\Sigma}$.

$$R/\varepsilon \int_0^\infty \frac{\Phi(E) \cdot \Sigma(E) \cdot dE}{\int_0^\infty \Phi(E) \cdot dE}$$

which is the "true" flux.

The energy spectrum of a thermal neutron beam (cadmium ratio >20, say) is usually more or less Maxwellian, in which case it can be assigned the characteristic temperature (T) of the equivalent Maxwellian - usually somewhat higher than the physical temperature of the moderator. T can be obtained directly by measuring the cross-section of a thin "1/v" absorber, or calculated from the energy spectrum of the beam, and when a "1/v" detector is used to measure the intensity of a Maxwellian flux

$$\Phi = R/\varepsilon \cdot \frac{\sqrt{\pi}}{2} \cdot \Sigma_{th} \cdot (T/293)^{1/2},$$

and T should be quoted.

Usually neither the characteristic temperature nor the energy spectrum is published and presumably not known, so one suspects that the "flux" quoted is merely $\Phi = R/\varepsilon \cdot \Sigma_{th}$, $-\Sigma_{th}$ being the reaction cross-section of the detector for neutrons of energy 0.0253 ev. Flux defined in this "lazy man's" way was given respectability by Westcott (J. Nucl. Energy, 2, 59-76, 1955), and is usually written $\hat{\Phi}$. Westcott pointed out that one is in fact including the $(E)^{1/2}$ variation of the detector cross-section in the definition of flux, and this convention simplifies some calculations, particularly those of reaction rates. So there are good reasons for using the "Westcott notation," but it should be stated when this is the case. The temperature of the equivalent Maxwellian spectrum is needed in Westcott notation only when calculating reaction rates in "non 1/v" absorbers, and in case the reader wants to do this, T should be given.

Specification of the γ ray beam associated with the neutron beam should be given similar attention, since "γ background" is often the factor limiting the contrast sensitivity attainable -

particularly with thick objects. The γ intensity, if published at all, is usually given as Γ mr/hr, which figure was obtained by placing a "health physics" monitor in the beam - one presumes. Even if precautions had been taken to remove all neutrons from the beam without intensifying the γ's, the reading is still suspect since "health physics" monitors measure γ "field" intensities, and are only correctly calibrated for neasuring γ beam intensities when the cross-sectional area of the beam is equal to that of the ionization chamber of the monitor and exactly aligned with it.

To specify the γ beam, measure the intensity with an ionization chamber monitor, with attention to the factors mentioned above, or by using film. Also measure or deduce the γ energy spectrum, which will be the "capture γ" spectrum of the shield and/or the moderator, with an average energy of $\sim$1 MeV typically. The γ intensity in photons/cm^2/sec can then be obtained (see e.g., ANL-5800, "Reactor Physics Constants," p. 657). The "n/γ ratio" of the radiographic beam can now be quoted as so many neutrons/photon, which is a useful "figure of merit" for the beam, and surely preferable to so many neutrons/cm^2/sec per mr/hr.

To summarize: when the performance attained in a n-radiographic system is published as a guide to other radiographers, the beam parameters which should be quoted are:

1. The neutron beam intensity, and whether "true" or "Westcott."
2. The temperature of the equivalent Maxwellian if a thermal beam is used, or the complete energy spectrum.
3. The intensity of the associate beam.
4. The average energy or the energy spectrum of the γ beam.
5. The divergence of the neutron beam, if the resolution attained is quoted.

NEUTRON RADIOGRAPHIC INSPECTION OF METAL ADHESIONS, ALLOYS, ACTIVE FUEL ELEMENTS, DIFFUSION OF H INTO Zr AND DIFFUSION OF H_2O - D_2O

K. Chountas and H. Rauch
Atominstitut der Osterreichischen Hochschulen
Wien, Austria

INTRODUCTION: This paper is a continuation of earlier studies in which we investigated particularly the recognition of defects in plastics behind thick steel plates [4]. The report describes improvement in experimental arrangements and further appropriate applications.

EXPERIMENTAL SETUP: The experiments were performed on a radial beam of the Triga Mark II reactor operating at 250 KW. The collimator is of the conical type with a 10 min divergent angle [11,12]. The input aperture is 15 mm and is defined by rings of Cd, Pb, and B_4C. The walls of the collimator are lined with B_2O_3 to reduce scattering. Collimated neutron fluxes are 3.1×10^5 n/cm^2-sec at 50 cm from the collimator outlet, and 2×10^5 n/cm^2-sec at 100 cm from the outlet. For active fuel element examination a cylindrical heavy concrete shield of 80 cm diameter is available. (See Fig. 1.) This has openings for the neutron beam and imaging foil, and the fuel element is inserted from the top. B_4C diaphragms are pressed against the sides of the element during examination. Neutron detection methods used are (1) transfer method for active fuel - dysprosium foil typically 30 min neutron exposure, transfer to Osray DW film for typically 1 hr; (2) direct method for all other applications - gadolinium foil (25μ) used with Osray DW film, typically 5 min exposure and with less than 5 per cent gamma ray effect.

The results given in this report refer to films exposed to the region where film density is proportional to exposure. They also refer to thin samples where the neutron beam attenuation is exponential. Film densities are measured with an accuracy on contrast (ΔD) of 0.008 units.

MEASUREMENT RESULTS

Metal Adhesions: Glue adhesions between pairs of metal plates were studied. Metals were Pb, Al, and steel, and thicknesses of individual plates were between 2 mm and 6 mm. The glue was of average thickness 0.2 mm. Different qualities of glue adhesive could be easily distinguished. (See Fig. 3.) Inhomogeneities of 24% in the glue layer itself could be detected, and this capability was independent of the metal type or thickness.

Alloys: Neutron radiography was used to study inhomogeneities in alloys. The thickness of samples was 3 mm. For Sn-Cd alloys containing 2.1 wt % Cd inhomogeneities of 1.1% (i.e. 2.1 ± 1.1%) Cd could be detected. (This is 0.028% of the total alloy density.) (See Fig. 4.) For Pb-In alloys with an indium content of 30% inhomogeneities of 0.8% (i.e. 30 ± 0.8%) In could be detected.

Hydrogenation of Zr: Above 547°C the α-phase of Zr transfers after absorption of small amounts of H into the β-phase. This β-phase readily absorbs H to transfer to the γ-phase. The hydrogenation process can be observed by means of neutron radiography. Zr samples (0.7 mm thick) were hydrogenated in a suitable quartz vessel in a pure H-atmosphere for different times and temperatures. Fig. 5 shows the results for 700°C over a range of hydrogenation times, and Fig. 6 shows the results for 6 hours over a range of temperatures. Effects of both temperature and hydrogenation time can be evaluated. For the 0.7 mm samples hydrogen concentrations of 2×10^{21} atoms/cm^2 could be detected, and this corresponds to a density difference of 0.056% of the entire sample.

Mutual Diffusion of Light and Heavy Water: An exact measurement of the diffusion properties $H_2O \rightleftarrows HOD \rightleftarrows D_2O$ permits statements concerning the structure of water [16]. Results obtained by neutron radiography can be compared with results by tracer methods [17], NMR methods [18] and inelastic neutron scattering experiments [19], where differences of 30% occur.

The diffusion was studied in the temperature range from 0°C to room temperature, using a cooling control stable to 0.2°C. The aluminum sample container had dimensions: thickness 5 mm, height 50 mm, width 50 mm. The lower half was filled with heavy water, and the a stratified layer of pre-cooled light water was carefully introduced by means of a U-shaped capilliary tube with the opening at the D_2O surface level. Fig. 7 shows the course of the diffusion at various temperatures. By measuring such neutron radiograph film densities with a photometer and comparing these with standard radiographs for known percentages of light water it was possible to obtain the experimental results of H_2O/D_2O concentration. The experimental course of the diffusion was compared (see Fig. 8) with the calculated diffusion using the diffusion coefficient calculated by the formulae of Wirtz [20]. The viscosities at the different temperatures were taken from the report [21].

A deviation between the experimental and theoretical diffusion characteristics in Fig. 8 indicates that the true diffusion coefficient is smaller than anticipated.

An appreciable diffusion of H into D_2O was still observed at 1°C (see Fig. 9) in spite of the fact that at this temperature the heavy water is solid (m.p. 3.82°C). A frequent proton exchange can be explained by the high entropy of ice (and see the neutron scattering data [22]). The neutron radiography measurements yielded a diffusion coefficient of $D = 3 \times 10^{-6}$ cm^2/sec. More exact measurements are still in progress.

INVESTIGATION OF ACTIVE TRIGA FUEL ELEMENTS

The fuel elements consisted of 92 wt % Zr hydride, 64 wt % U-238 and 1.6 wt % U-235. The neutron attenuation is caused mainly by the U-235, and inhomogeneities in its distribution can be determined by neutron radiography to an accuracy of 1%. Similarly, inhomogeneities in the burnup can be determined to an accuracy of 1.1 wt %, this value taking into consideration the accumulation of long-lived fission products ($T_{\frac{1}{2}} >$ 3 months) and build up of Pu-239. The fuel element shown in Fig. 10 was removed from the innermost ring of the reactor core after 21 MW-days of reactor operation, and the neutron radiography was performed after 6 months cooling.

DISCUSSION

The above examples demonstrate a variety of applications for neutron radiography. In particular entirely novel investigations are possible for the diffusion of hydrogen in heavy metals. The studies of the diffusion of light water in heavy water by neutron radiography shows that the mean displacement of hydrogen can be determined, and such studies can be of interest in other hydrogen containing substances (particularly in organic materials). If different H-nuclei are bound together in a compound with variable strength then it is possible to establish how much the different H nuclei contribute to the diffusion. The diffusion of the H nuclei frequently differs very much from the diffusion of the entire molecule.

[1] Kallmann, H.: Research 1, 254 (1948)
[2] Berger, H.: Neutron Radiography. Amsterdam: Elsevier Publ. Comp. 1965
[3] Neutron Radiography Newsletter 1–7 (Ed. H. Berger, J. P. Barton, K. Ogawa). Evanston, USA (1964–1968)
[4] Rauch, H., und G. Saringer: Materialprüfung 8, 134 (1966)
[5] Berger, H., und I. R. Kraska: Mater. Evolution 22, 305 (1964)
[6] Schultz, A. W., und W. Z. Leavitt: Mater. Evolution 23, 324 (1965)
[7] Barton, J. P.: Proc. Conf. Phys. a. Nondestructive Testing Dayton, USA (1965)
[8] Berger, H., H. H. Talboy und J. P. Tylka: Nucl. Sci. a Eng. 18, 236 (1964)
[9] Berger, H., und W. N. Beck: Nucl. Sci. a. Eng. 15, 411 (1963)
[10] Barton, J. P.: Neutr. Radiogr. Newsl. 7, 11 (1967)
[11] Saringer, G.: Dissertation. Atominstitut Wien, Austria (1966)
[12] Barton, J. P., und J. P. Perves: Brit. J. Nondestr. Testing 8, 79 (1966)
[13] Berger, H.: J. Appl. Phys. 33, 48 (1962)
[14] Ells, C. E., und A. D. McQuillan: J. Inst. Metals 85, 89 (1956)
[15] La Grange, L. D., L. J. Dykstra, J. M. Dixon und U. Merten: General Atomic GA-760 (1959)
[16] Egelstaff, P. A.: An introduction to the liquid state. London, New York: Academic Press 1967
[17] Wang, J. H., C. V. Robenson und I. S. Edelman: J. Amer. Chem. Soc. 75, 466 (1953)
[18] Simpson, J. H., und H. Y. Carr: Phys. Rev. 111, 1201 (1958)
[19] Larsson, K. E.: Experimental results on liquids. In: Thermal Neutron Scattering (Ed. P. A. Egelstaff). London, New York: Academic Press 1965
[20] Wirtz, K.: Z. f. Elektrochemie, Ber. D. Bunsenges. f. Phys. Chem. 58, 109 (1954)
[21] Reactor Handbook (Ed. C. R. Tipton). Vol. I, p. 842 New York: Interscience Publ. 1960
[22] Bacon, G. E.: Proc. Roy. Soc. A 246, 78 (1958)

Figures

For Figs. 2-7 and 10, which are reproductions of radiographs, captions only are given in this summary. Readers are referred to the publication of the full paper in Atomkernenergie for these figures.

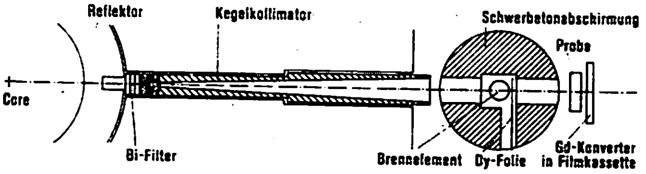


Fig. 1: Sketch of the experimental setup

Fig. 2: Radiograph of a part of the neutron beam at the measuring table (the width of the figure corresponds to 9 cm) *

Fig. 3: Radiograph of two 3 mm thick steel plates adhered to by three different adhesive substances (a, b, c) *

Fig. 4: Radiograph of a Sn-Cd(2,1 %)-alloy with a thickness of 3 mm *

Fig. 5: Radiograph of Zr-samples, hydrated for various times at 700 °C. (Duration of the hydration from left to right 0, 3, 4, 5 and 6 hours) *

Fig. 6: Hydration of Zr at 650, 700, 750 and 800 °C (f. l. t. r.) for a duration of the hydration of 6 hours *

These investigations are not limited to the liquid phase, but can be carried out also with solids. Osmotic and biological processes can be studied by this method, and pulsed reactor methods with short exposure times (approximately 60 msec) could be of importance for studies of chemical reactions.

Fig. 7: Radiographs of the diffusion H_2O-D_2O at 10, 15 and 20 °C (from top to bottom) after definite times: 15, 30 min, 1, 2, 4, 6 hours (from left to right) *

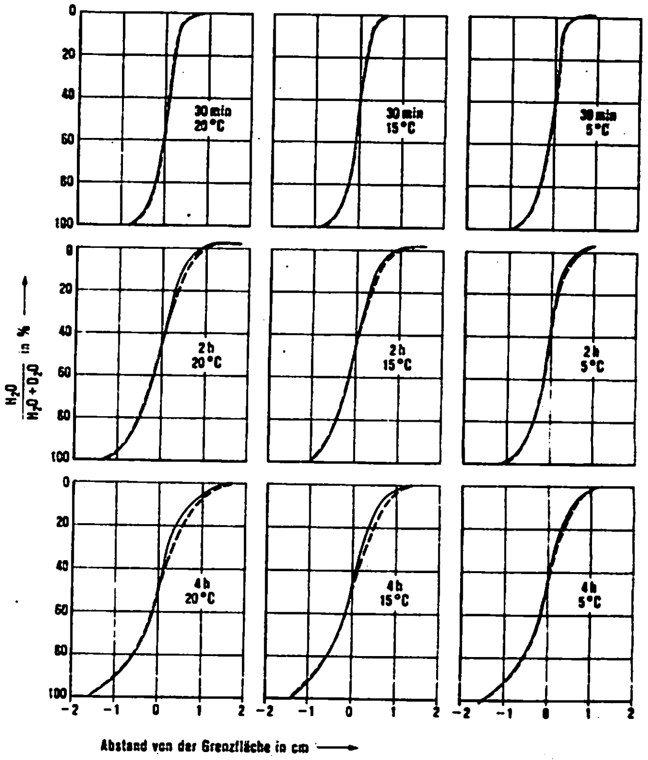


Fig. 8: Comparison of the measured (solid lines) to calculated (dashed lines) diffusion of water at various temperatures and diffusion times

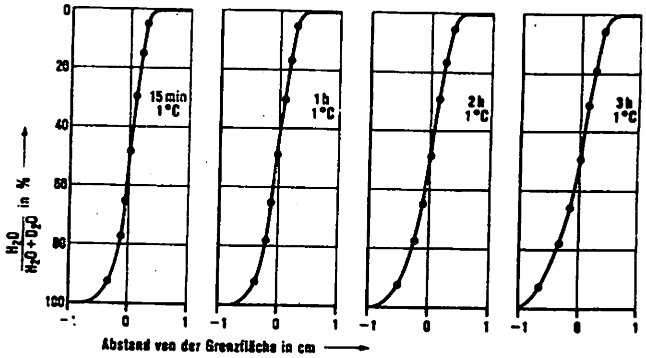


Fig. 9: Diffusion of H at 1°C into D_2O ice

Fig. 10: Radiograph of an active TRIGA-fuel element showing the inhomogeneous burn up of U 235 *

SOME THOUGHTS ON NEUTRON RADIOGRAPHY STANDARDS

J. P. Barton

INTRODUCTION

John Smith has been operating a neutron radiography facility, and one thing he can report from experience is that his neutron radiography provides 100 per cent visibility of faults in item A. Tom Brown, in another establishment, also needs to inspect items of type A. Is there any way he can know that a certain neutron radiography facility constructed at his place will also provide 100 per cent detection of these faults? The words "neutron radiography" are the same, but there may be differences.

Pierre Dupont has a reactor available for neutron radiography, and can choose between a thermal column beam, a tangential beam, a radial beam, and various filtered beams. Clearly each set up has its own characteristics and peculiarities, but how can he indicate their performance in simple direct terms, and how can Hans Schmidt compare his own set-up which is based on a Van de Graaff accelerator?

One, first step is to quote the flux. John Smith has a neutron radiography facility giving a flux of 10^8 n/cm^2-sec at the object; Tom Brown designs his to give 10^5 n/cm^2-sec. This is useful information but it is not sufficient. They can define the basic collimation ratio. This is one more step, but there are other factors: the design and efficiency of the collimator, the neutron spectrum, the gamma ray spectrum, the relative intensities of neutrons and gammas, the characteristics of the detector combination, the positions of scattering objects --- they all may have an effect on the radiographic performance. It would be difficult to measure absolutely and interpret all the influential factors.

What can they do? One possibility is to show a neutron radiograph. *"This arrangement will show the plastic insulation on the capacitor connection in my article B."* That is a step forward, and would perhaps be sufficient if everybody else had identical articles "B", and if all neutron radiographers were concerned with the same type and size of object. Is there a case, however, for having a standard test object designed for neutron radiography?

Some care about terminology is warranted since this is a relatively new field. In this article we will refer to a test object designed for the above mentioned purposes as a *"system IQI"* (System Image Quality Indicator).

In addition to a system IQI there may be other needs for standards in neutron radiography. These may be different both in design and objective.

The quality and reliability Handbook H.55 on Radiography(1) states prominently and repeatedly *"A radiograph not bearing a penetrameter image has little value, and should not be interpreted except in very rare cases."* The same message is conveyed in most authoratative x-radiography manuals. If this is true for x-radiography, is it also going to be true for n-radiography? In this paper we will refer to this type of neutron radiography test object as an *"object IQI"* (Object Image Quality Indicator).

The system IQI may be quite large (the size of a typical object) and should be capable of precise quantitative measurements. The object IQI should be small, and should meet the following requirements:

1. It should be capable of placement in the corner of each radiograph, or behind different sections of the object being radiographed.

2. Readings should be simple and unambiguous (not requiring instrument readings such as densitometer traces).

3. A system of identification might be incorporated, such that each radiograph can be numbered automatically.

4. It should be inexpensive to manufacture, easy to standardize, easy to apply, and versatile as to application.

5. It should provide a simple check on radiographic quality variations due to a) facility and technique, b) object composition and geometry, c) unexpected variations such as film development etc.

There will be a relationship between object IQI sensitivity and the neutron radiographic flaw sensitivity. This relationship will probably be complex and incompletely understood. However, improved object IQI sensitivity should invariably be a sign of improved radiographic quality.

LESSONS FROM X-RADIOGRAPHY

Clearly the mechanisms and objectives of n-radiography and x-radiography are so different that we cannot simply borrow the same x-ray penetrameters. However, we should certainly look carefully at the history of x-radiography to see what lessons there may be. "Let the shipwrecks of others be our landmarks". Authors writing on x-radiography point out two areas of confusion in their field. Both were probably caused by lack of communication between workers in the early days of radiography.

1. Standardization. A first lesson can be learned from the confusing number of different x-radiography penetrameters adopted as standards by different groups. In the words of one author(2) *In the past, authorities in various countries have produced specifications for image quality indicators suited to their own needs and having little or no regard for what was being used elsewhere."* Even within a single country, and for x-radiography of a single material (0.1-2 in. steel), O'Connor(3) has pointed out that due to different codes a so-called 2 per cent sensitivity may vary from 2 to 24 per cent equivalent sensitivity. X-radiography penetrameters have been adopted which consist of steps, plates, holes, balls, grooves or wires of all shapes and sizes. Feaver(4) has shown how the relative performances of three widely used standards can change abruptly with changes in parameters such as film grade or image density.

2. Terminology. A second general lesson to be learned from x-radiography concerns the ambiguity of terminology which has grown into common usage. It is for this reason that we have devoted space in this article to discussion of the terms we have introduced.

Halmshaw(5) teaches that we should distinguish between the terms *"radiographic sensitivity"* and *"radiographic quality"*. The term *radiographic sensitivity* should be normally used to refer to the smallest defect detectable, whereas *radiographic quality* may include characteristics of particular interest in a given application, such as latitude or visibility of a certain type of detail other than the smallest. We also note that the term *"penetrameter"*, as used in x-radiography, is considered to be a misnomer. The word probably was derived historically from the medical term *"penetrometer"*, but the name does not describe the function. Since neutron radiography standards will be quite different to those of x-radiography, we therefore take the opportunity to avoid the word penetrameter and to use the term *"IQI"* consistently for the neutron devices.

The US Radiography Handbook H.55(1) also teaches us to be wary of the term *"radiography standards"* since this is sometimes used in x-radiography to refer to entirely different things,namely a) documents giving details of specifications and b) radiographs of standard specimens showing faults of predetermined seriousness. In this article we use the term *"reference radiographs"* to refer to the latter type of standard, as is the practice in the ASTM literature.(6)

PRELIMINARY PROPOSALS

It would seem, therefore, that there is a need for three types of standards in neutron radiography:

(1) System IQI.
(11) Object IQI.
(111) Reference Radiographs.

The third category, reference radiographs, is clearly something for each group of users to build up by experience after performing neutron radiography of particular types of object and setting appropriate acceptance and rejection conditions. This category is not discussed further in this article.

If it is agreed that there is a need for a system IQI and for an object IQI, one way to proceed would be for several interested workers to independently develop and put forward proposed solutions, and then, at some later stage, these various proposals would be compared. Neutron radiographers could then decide, at a future international meeting, whether they wish to adopt one system or perhaps an amalgation of the better parts of alternative systems. It is with this idea in mind that we have developed one preliminary "system IQI" and one preliminary "object IQI". These IQI's will be sent, in time, to all interested neutron radiographers who may wish to try them and perhaps suggest modifications or alternative approaches.

SYSTEM IQI

Details of the preliminary system IQI are given in Figure 1. It takes the form of a stack of thin aluminum support plates separated by spacer rings around the support bolts in the four corners. The spacing may be easily changed from small (8 mm) to large (14.5 mm). Each support plate holds a test strip of type B arranged to appear side by side on the radiograph, but with each identical test strip at increasing separations from the imaging plane. These test strips indicate the combined effects of geometric unsharpness, neutron spectrum, gamma content etc. Each strip includes a series of plastic wires (providing low contrast), a series of cadmium wires (providing high contrast), and a series of holes in 0.5 mm cadmium.

The support plate nearest to the imaging plane holds both a test strip of type B and a test strip of type A. The test strip A includes small squares of different absorbers of side dimension 5 mm such that densitometer readings may be conveniently taken on the radiograph. The relative contrasts of these absorbers give a measure of the thermal neutron to fast neutron ratio, and also the relative gamma effect of the neutron radiography facility in conjunction with the detection system in use. Adjacent to the absorbers is a cadmium strip drilled with small holes arranged progressively closer together. This provides a test of the inherent unsharpness of the detection system in use, and microdensitometer traces across the cadmium straight edge can provide a second test.

This preliminary system IQI has been used with a small range of reactor beams (see Table I). It does seem to give an immediate impression of the characteristics of the neutron radiography facility, and it enables a large number of quantitative measurements to be read. In the interest of brevity we give here just two examples:

The plot of Figure 2 was formed by arranging the absorbers such that the results for one collimator (c) would be in a straight line. It was then found that each of the other three facilities also provides straight lines, though of different slopes. This result was obtained using the gadolinium foil direct exposure technique. When the indium transfer technique was used, the results for all collimators were found to lie in one single straight line.

Figure 3 is a plot of plastic wire visibility versus separation from the imaging plane. It clearly shows how for small separations, corresponding to small object thicknesses, the poorly collimated beams are preferable due to advantageous neutron spectrum and neutron to gamma ratio, whereas for large separations the geometric unsharpness becomes important and highly collimated beams are of value.

OBJECT IQI

The proposed object IQI is, of course, smaller and simpler, but it does incorporate some of the features of the system IQI. It consists of a single plate of area 40 x 20 mm (1-1/2 x 3/4 in.). The aluminum support plate contains a row of small absorber squares (lead, indium, cadmium, plastic, gadolinium, dysprosium) covering a range of thicknesses and arranged in order such that for a "normal" neutron radiography arrangement they read in increasing order of contrast from one end of the line to the other. This order of grayness on the radiograph can be checked at a glance. Discontinuities such as high lead contrast would indicate a high gamma component in the radiograph make up, high indium contrast might indicate a high resonance to thermal ratio, whereas high plastic contrast as compared to cadmium would indicate a high fast neutron effect. The relative contrasts of indium, gadolinium, dysprosium provides a record of what detector screen was used. The designed object IQI also contains the cadmium strip drilled with groups of holes (for easy reading of high contrast radiographic definition), and series of high contrast wires (cadmium) and low contrast wires (plastic).

SUMMARY

Some tentative ideas have been put forward for a system IQI and also for an object IQI, but it is emphasized these are only the preliminary suggestions of one individual. Alternative suggestions from other workers are encouraged. A main point of the article is to draw attention to the desirability of working toward an eventual adoption of a single set of standards, thus avoiding confusion which had been associated with the early growth of x-radiography.*

References

1. Quality and Reliability Assurance Handbook H.55 - Radiography, U. S. Department of Defence, Washington, D. C.
2. Atherton, D., Brit. J. of Non-destructive Testing, Sept. 1967, pp. 76-79.
3. O'Connor, D. T., and Criscuolo, E. L., ASTM Bull. No. 213, 53 (1956).
4. Feaver, M. J., Non-Destructive Testing, Vol. 1, No. 3, Feb. 1968, pp. 173-182.
5. Halmshaw, R., Physics of Industrial Radiology, New York, American Elsevier Pub. Co., Inc.
6. ASTM Methods and Development. Materials Research and Standards, Vol. 9, No. 5, May 1969, pp. 14-15.

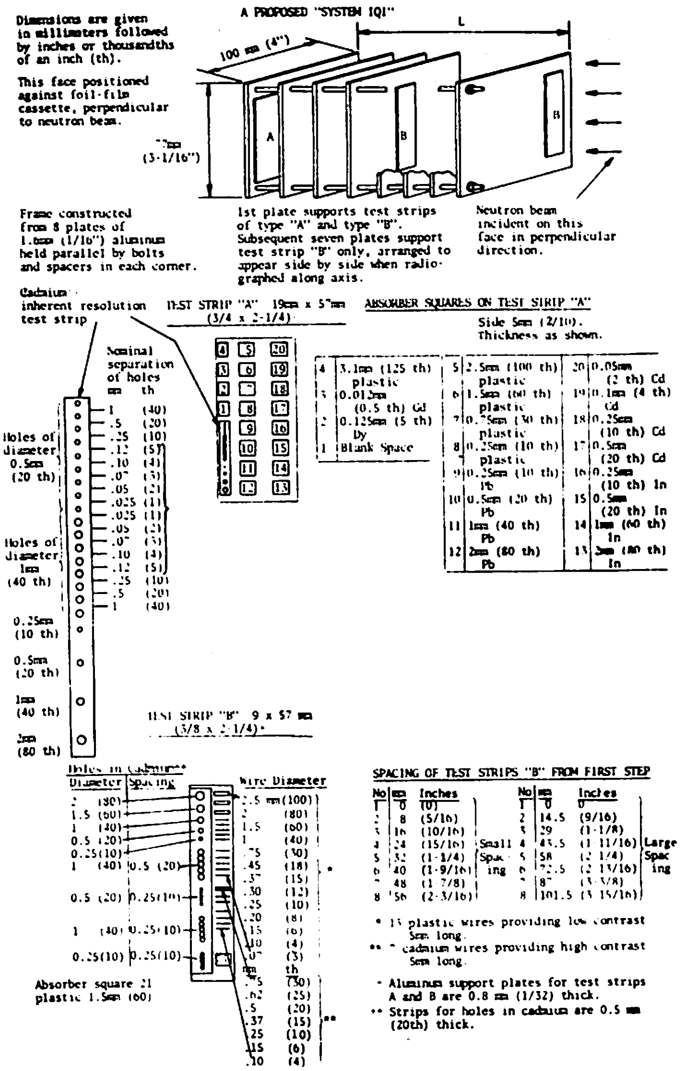


Fig. 1

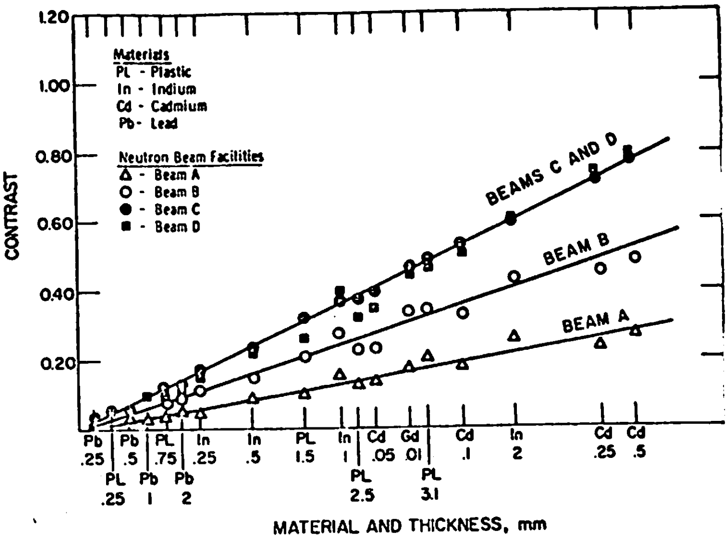


Fig. 2 Radiographic Contrast for Different Absorber Materials and Thicknesses, and for Different Neutron Beams. (Gadolinium foil, Kodak Single R film, direct exposure.) The locations of the materials along the abscissa axis were chosen so as to make the plot for Beam C linear.

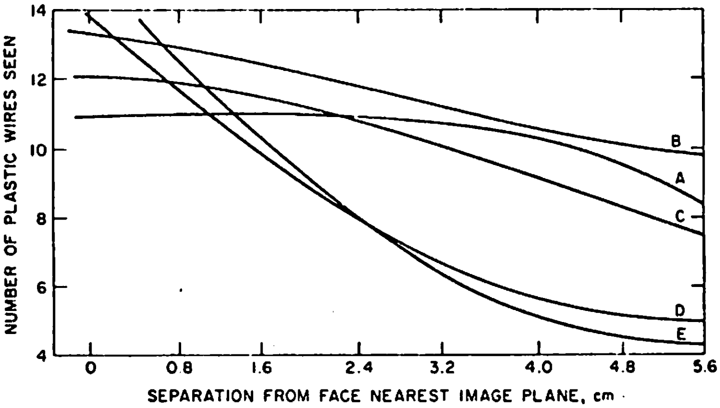


Fig. 3 Visibility on a Neutron Radiograph of Plastic Wires as a Function of Separation of the Wires from Face Nearest Image Plane for Different Neutron Beams. (Gadolinium foil, Kodak Single R film, direct exposure.)

TABLE 1. Neutron Beams Used to Evaluate Test Standard

Beam Designation	Input Aperture Dimensions (cm)	Beam Length (cm)	Dimension of Uniform Beam Area at Output (cm)	Thermal-neutron Flux (n/cm^2-sec)	Cadmium Ratio, Au (Bare) / Au (Cadmium)	Gamma Intensity (R/hr)
A	1.27[a]	224	15[a]	2.3×10^6	1.4	280
B	2.54[a]	224	15[a]	8.9×10^6	1.7	370
C	5.08[a]	224	15[a]	3.5×10^7	2.1	560
D	10.16[a]	224	15[a]	1.4×10^8	2.2	1,700
E	15.24[a]	224	15[a]	3.6×10^8	2.5	2,200

[a] Diameter.

ON THE ECONOMICS OF NEUTRON PRODUCTION*

M. R. Hawkesworth
University of Birmingham U.K.

A survey of particle accelerators on the market that can be used for neutron generation was recently published.[1] The salient characteristics of each generator including basic price were listed, and a plot showing the relation between maximum output intensity and basic cost was given (Fig. 1). Although giving a superficial view of the cost of neutron production, the diagram generated some interest.

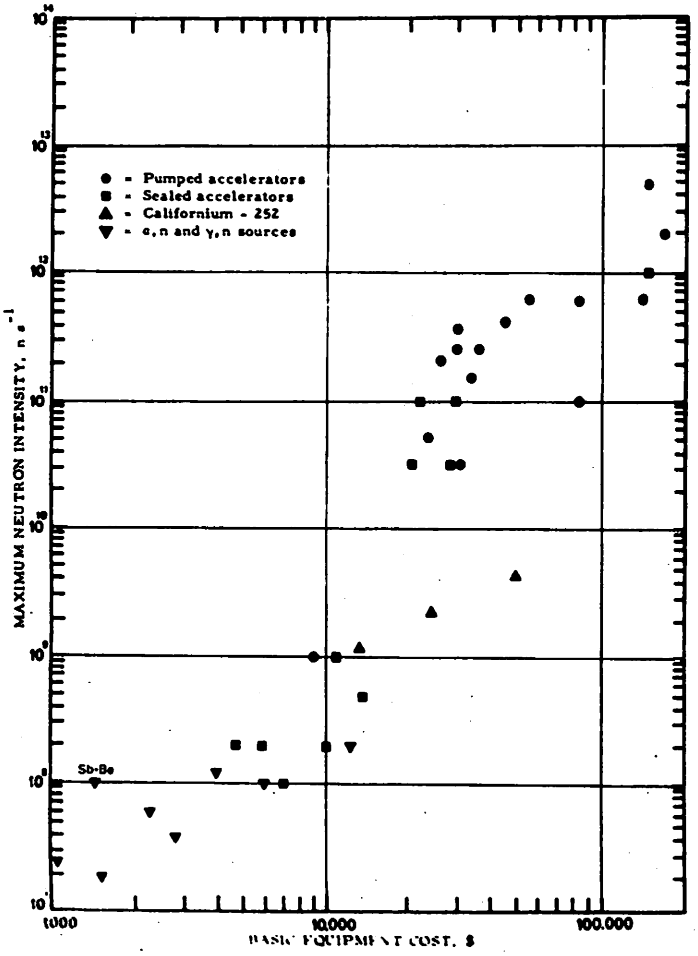


Figure 1 The basic equipment cost (Summer 1971) of sources of neutrons in relation to their maximum intensity.

An informal publication like the Newsletter seems an appropriate place to present an extension of this work to the cost of thermal neutron flux production. Radioisotope and nuclear reactor sources can then also be brought into a single picture. Such a survey is an essential prelude to more accurate estimates of the cost of neutron beam production for radiography.

The maximum thermal neutron fluxes that can be produced may be related to the equipment costs if the "thermalization factor" (source intensity ÷ peak thermal flux) appropriate to the various types of source are known. Table 1 presents data for sources used with water moderator. This data has been used to prepare Fig. 2.

Table 1

Neutron Source	Thermalization Factor
D-t	600*
D-D	200
Am-Be	200
Sb-Be	45
^{252}Cf	100**
D-Be	100

*Rounded figures from recent Birmingham measurements

**Rounded figures from the literature.

---

* The Neutron Radiography Program at the University of Birmingham is supported by the Science Research Council.

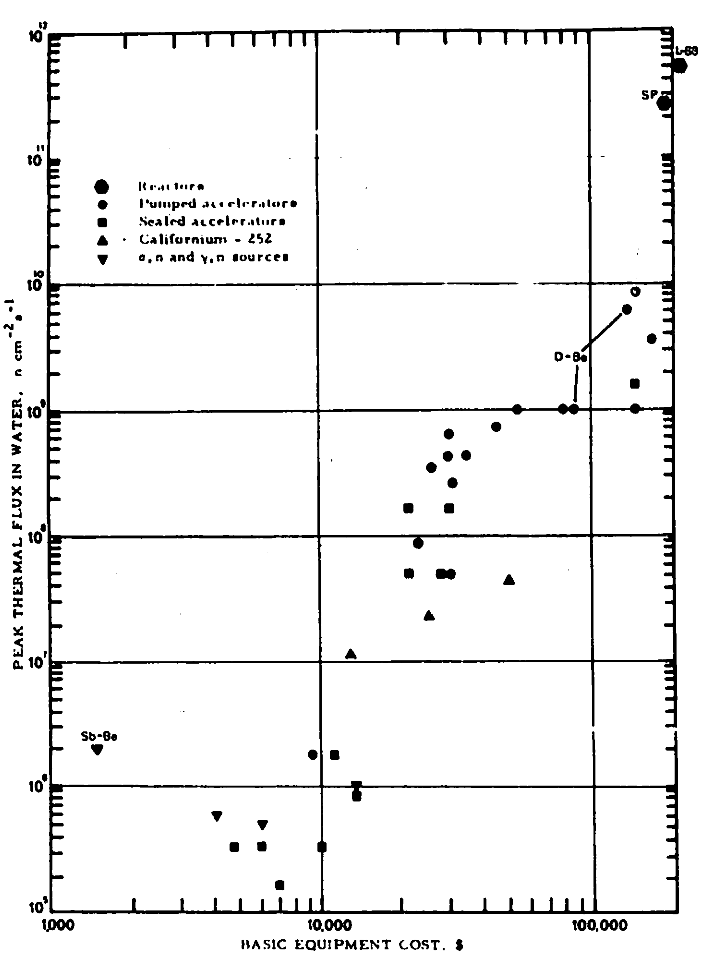


Figure 2. The basic equipment cost (Summer 1971) of sources of neutrons in relation to the maximum thermal neutron flux they can produce in water.

Rounded figures have been used since, in any practical source-moderator system, voids and metal near the source will depress the flux to an uncertain extent. The use of polythene or transformer oil as a moderator can improve thermal fluxes by about 20%, and thermal fluxes from D-T sources can be increased by a factor of 2 or more by surrounding the source with some 5 cm of uranium (natural or depleted).

The radioisotope costs used are those quoted by the Radiochemical Centre. Two reactors are included in Fig. 2, the L-88 offered by Atomics International and Slowpoke (SP) advertised by AECL. Generators produced by Accelerators Incorporated, Elliott-Automation, High Voltage Engineering, Kaman, Multivolt, Ortec, Philips, Radiation Dynamics and Tunzini-SAMES have been considered.

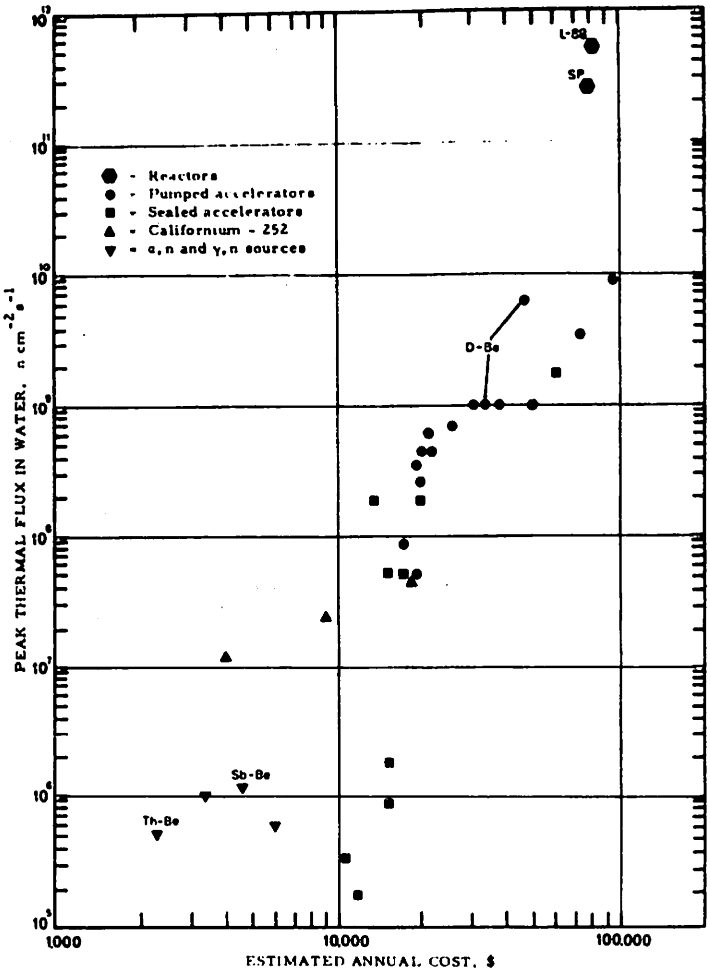


Figure 3. The estimated annual cost (1971) of neutron sources in relation to the maximum thermal neutron flux they can produce in water.

Comparing Fig. 2 with 1, it will be noticed that a more favourable view is presented for radioisotope sources, (particularly californium) and the D-Be accelerators (HVEC Van de Graaff machines).

The advantage tilts still more towards californium when the thermal neutron fluxes are related to annual operating costs (Fig. 3). Annual cost estimates depend strongly on the "ground-rules" chosen for their estimation. In our case the rules were simple. They may be summarised as follows. All capital charges (capital plus interest at 8%) are written-off in equal installments over 5 years. In such a short time, usual for scientific equipment, the interest rate has little effect on overall costs. A small contribution to operators salary has been allowed: $20,000 for the reactors, $10,000 for pumped generators, \$5000 for sealed generators and zero for radioactive sources. An annual work load of 500 hours at full intensity was assumed for the generators, with target costs at 2×10^{14} neutrons per \$ for the D-T machines. A minimum target cost of \$1000 was assumed for D-T, D-D and D-Be machines. One replacement tube per year was assumed for the sealed generators. The figures do not include allowance for other uses such as activation analysis, therapy, x-radiography, neutron research and teaching. Nor do they include charges for housing and shielding. Fuel charges at \$10,000 per year were included in the reactor costs, but no licensing charges were added.

The data of Fig. 3 indicates that for the equipment contribution to the charge for a radiograph to be < \$20 the number of radiographs taken per year must range from > 200 with the lower intensity sources to > 5000 with small reactors. Readers might like to comment on the various figures in this note. Are they realistic at this time?

REFERENCE

1.)L. Holland and M.R.Hawkesworth, "Low Voltage Particle Accelerators for Neutron Generation," Nondestructive Testing, October 1971.

#13. 1974

1974 REVIEW

J. P. Barton

Nuclear Fuels

Neutron radiography is being increasingly cited as an important method for examination of nuclear fuel both before and after irradiation. For example, at the recent "Fuels Technology" session of the ANS winter meeting, two of the six papers depended on neutron radiography.

A recent report received from Dr. Alan Ross of AECL (Fuels Materials Branch--Chalk River) shows the variety of application for which fuels neutron radiography is now being used: inspection of unirradiated fuel for general physical condition and sometimes also for U-235 or plutonium enrichment uniformity; inspection of irradiated fuel to determine the extent of cracking, fragmentation, void formation, swelling, redistribution of U-235 or plutonium, hydriding of zirconium alloy clad, etc. The report states that neutron radiography is now used routinely at Chalk River to follow the irradiation behavior of many different types of fuel element. Hydriding of fuel clad which is exposed to light water either during or after irradiation provides one powerful neutron radiographic method for detecting defective elements.

Gerard Farny, of Saclay, France, spent some days here at OSU in August discussing neutron radiographic techniques for examination of light water reactor fuel. He is constructing a faciltiy using the ISIS reactor to inspect large quantities of this full length fuel. This reactor operates at nearly 1 MW, and because it is below ground, a large pit has been excavated to accommodate a horizontal beam facility. Large quantities of power reactor fuel will be inspected using automated processes. Track etch imaging is being used with cellulose nitrate sheets of 10 meter length. Reports state that the high resolution of this track exposure technique more than compensates for the rather low inherent contrast, such that the method appears to be competitive with traditional (foil activation transfer) techniques.

A report on neutron radiographic uses for nuclear fuel creep measurement was recently issued by Ron Matfield at AERE Harwell (Report AERE R-6822). Ron has now moved from the neutron radiography field to other tasks, but the variety of fuels examination applications at Harwell continues under the direction of Tom Robertson. A particularly impressive paper at the Birmingham meeting was that describing neutron radiography capabilities at the 5 MW Herald Reactor at Aldermaston. Four separate beams have been used--cold, thermal, epithermal and a monochromator facility.

Recent activities for fuels neutron radiography at the Karlsruhe Center have been published in a September 1973 report KFK 1841 by H. Schulken. This is a substantial report, about 100 pages long and includes some 50 tables and figures. Also in Germany, Dr. M. Greim of Kernener Gieverwertung, Hamburg, has described the use of two reactor facilities there for fuels development work. Applications include studies of burnable poisons.

The Japanese are, of course, operational in fuels development. One center there to recently announce installation of a neutron radiographic facility is the Tokyo Atomic Industrial Research Laboratory.

Don't miss the paper by Heikki Reijonen and colleague P. Jauho of the reactor laboratory, Technical Research Centre, Helsinki, Finland. Published in 1973, it is entitled, "On the Determination of Pu^{239} and Pu^{240} from Reactor Fuel by Neutron Radiography with Filtered Neutron Beams."

J. Juttel and J. Remouille of Grades, S. A. Steinfort of Luxembourg have been working on reactor fuel neutron radiography for the electrical utilities of the Benelux countries, and a paper is scheduled for publication soon in Kernenergie-Atompraxis.

From the USA, some news on neutron radiography for nuclear fuels is as follows:

At the Aerojet Nuclear Corporation Center at NRTS Idaho, Lowell Miller is currently setting up a new neutron radiography facility for examination of reactor fuels. This will be based on a reactor source--the Active Reactor Materials Facility.

Ken Kok, of Battelle Columbus, has prepared a written report of the recent fuels examination activities at that center. Of the many types of fuels examined one of particular interest has been the examination of light water reactor fuel for densification and related phenomena.

Darrel Cutforth, working with the EBR-2 reactor and the hot fuels examination facilities group at Argonne National Laboratory, Idaho Falls, is performing considerable neutron radiographic examination using the TREAT reactor facility. A paper related to some of this work is "Dimensioning Reactor Fuel Specimens from Thermal Neutron Radiographs," by D. C. Cutforth, Nuclear Technology, Vol. 18, April 1973.

The NASA have now shut down the Plumbrook reactor, but Larry Thaler reports there is still a considerable quantity of neutron radiographic data on fuels examination which he plans to write into reports. Some recent papers from that center are: "The Measurement of Capsule Heat Transfer Gaps Using Neutron Radiography," NASA TM X-67920 by L. A. Thaler; (published in Materials Evaluation 32, No. 3, March 1974, p. 57-62 and "Applications of Neutron Radiography to Vapor Transport Fuel Pins," by C. D. Lanzo and D. C. Winterich. Trans. Am. Nuc. Soc., July 1972. One topic investigated extensively at the Plumbrook Center is the use of standards for dimensional measurements of fuel swelling and clad gap changes. Results of an enquiry into possible needs for USAEC-RDT standards in the field of neutron radiographic examination of fuel have been prepared in report form by J. P. Barton, Oregon State University.

One of the main questions in the Fast Breeder Reactor Programs is "How will the fuel material react to different burn up conditions?" Therefore, not surprisingly, special neutron radiography facilities have been (or are being) installed.

In France, two of the special neutron radiography Mirene reactors, developed at Valduc, have been installed and are now in routine operation for breeder reactor fuel inspection. One is at Cadarache for the Rapsodie fast reactor fuel, and one is at Marcoule for the Phenix fast reactor fuel. In the U.K., the DFR and PRF (Prototype Fast Reactor) both at Dounraey are served by an on-site neutron radiography facility using an Elliot P-Tube neutron generator. Don Shepard is working on this facility and he reports that it is now operating satisfactorily.

In the USA, the FFTF reactor (Fast Flux Test Facility) is under construction at Richland, and Westinghouse Hanford Co., who are managing this project for the USAEC, have recently made plans to install a 250 KW Triga reactor for the neutron radiographic examinations. Charles Jackson, Jr., is the man in charge of the neutron radiography plans there. Meanwhile, some of the first deliveries of FFTF fuel rods have been examined using neutron radiographic techniques at the General Electric Vallecitos Nuclear Center. Each of the 700 rods in the recent batch were neutron radiographed in six angles of orientation.

At the time of writing, we note that the Phoenix fast breeder demonstration plant in Marcoule, and the PFR plant at Dounraey have both recently begun operation. The next steps could be demonstration fast breeder power plants in the 1000 MW range.

Scintillator Screens

Considerable interest exists in obtaining improved scintillator converter screens for neutron radiography.

At CEN Grenoble, VuHong and colleagues have developed a method for improved ZnS(Ag)-Li^6F screens based on the use of a monomer plastic binder which is polymerized under gamma radiation.

At the Bhabha Atomic Research Centre in India, work has been performed on various types of granular scintillator containing Li^6 or B^{10}. A report entitled, "Slow Neutron Scintillators for Neutron Radiography," has been prepared by R. S. Udyauar, N. C. Jain and Y. D. Dande of that laboratory.

A paper by C. A. Hunt entitled, "A New Method of Shortening Exposure Times in Neutron Radiography," was published in the British Journal of Non-Destructive Testing, March 1972, pp 57-58. It described the use of a phosphor screen between dysprosium foil and film in the transfer imaging process.

K. L. Swinth has prepared a report, "Imaging Techniques for Low Flux Neutron Radiography." Ken was at Battelle Northwest Laboratories when the work was done, but his present address is Laboratory of Nuclear Medicine, UCLA, 900 Veteran Avenue, Los Angeles, California 90024. Also note Ken's work on cooling of scintillator-film combinations reported in Trans. Am. Nuc. Soc. 17, p. 90, 1973.

The Oregon State University neutron radiography group has compared several scintillators including gadolinium oxy-sulphide, gadolinium oxy-bromide, lithium glass and a number of home-made scintillators. For thermal neutron radiography, where lowest neutron fluence is not of prime importance, the gadolinium scintillators appear to have a distinct advantage due to fine resolution. R. H. Bossi is working to develop scintillators optimized for transmission orientation usage and with the short decay times necessary for high speed motion neutron radiography.

Both R. H. Bossi at Oregon State, and M. R. Hawksworth of Birmingham University have been studying the effects of statistical limitations on neutron imaging using low neutron exposures. One important result apparent from both independent sets of work is that signal to noise ratio should be independent of film contrast when the statistical effect is the controlling limitation.

At Reed College, Portland, Oregon, W. L. Parker and J. C. Rau have been working on scintillator screens for neutron radiography, and one idea being explored there is the use of bunched fiber optics with lithium glass scintillator fibers for thermal neutron imaging.

A. R. Spowart and I. R. Coates at Paisley College of Technology, Scotland have been studying the behavior of granular and glass scintillators over a range of temperatures from -190°C to +100°C. As a result of these studies, the importance of ultra pure scintillator constituents has been emphasized, and screens with improved light output have been tested.

Metal Foil Converters

Reports of progress on metal foil converters at McMaster University, Ontario, Canada, are: "The Detection Process in Neutron Radiography," by B. K. Garside and A. A. Harms, J. Appl. Phys. 42, 5161 (1971), and "The Role of Internal Conversion Electrons in Gadolinium-Exposure Neutron Imaging," by A. A. Harms, J. Appl. Phys. Vol. 43, 3209-3212 (1972).

N. C. Jain of the Bhabha Centre in India is working along similar lines with special attention being paid to the activation transfer technique.

In Russia, N.D. Tyufyakov, A. S. Shtan and V. S. Yaskevich of UNIIRT Moscow, have also been considering the theory of metal screen converters and a paper, "Optimization of Detector Parameters in Neutron Radiography," was published in the 7th International Conference of NDT.

Also from Russia, note the work of V. I. Gubunov and G. S. H. Pikarsky of SRIET, Tomsk, "Fast Neutron Defectoscopy," published in the same conference proceedings. The paper considers radiography advantages for fast neutrons for examination through 4 to 8 inches of dense metal such as uranium or lead.

Track Etch Detectors

The work of G. Farny at C.E.N. Saclay concerning the use of track etch neutron radiography has already been mentioned under the nuclear fuels section. The Kodak-Pathe Company at Vincinnes, Paris, France has done considerable work on preparation of track etch materials for neutron radiography and the person to contact there is J. Barbier.

Two meetings of the American Nuclear Society have featured sessions on general track etch techniques. See Trans. Am. Nuc. Soc., Vol. 13, 1970 (two sessions), and Trans. Am. Nuc. Soc., Vol. 15, 1972 (three sessions). There is also a paper by J. Morley entitled, "Two New Methods to Increase the Contrast of Track-Etch Neutron Radiography," NASA-TM X-67947 and a paper by H. Berger, "Radiography with Track Etch Detectors," proceedings of the seventh international conference on Nondestructive Testing.

Other Detection Systems

A multi-wire proportional chamber for neutron radiography has been developed by Kenneth Valentine, Selig Kaplan and colleagues at the University of California, Berkeley. The converter plate is boron and individual neutron interactions are recorded positionally by the cross grid of wires and a delay-line readout. The system can handle up to 6 x 10^4 signals per second from the 500 sq. cm. active area. The grid resolution is 2 mm. Papers on this have been presented at the IEEE Nuclear Science Symposiums in San Francisco, November 1971 and November 1973. (See IEEE Transactions on Nuclear Science NS-19, No. 1, Feb. 1972)

Work on a different proportional counter device that uses a grid of 1 mil diameter pyrolytic carbon coated quartz fibers on 2.5 mm centers has been conducted by K. L. Swinth and J. C. Crowe at Battelle Northwest Laboratories. Best results were obtained with a Li^6F converter layer. Papers on this work have also been presented at the IEEE Nuclear Science Symposiums in San Francisco, November 1971 and November 1973.

A detection system suitable for neutron scanning has been made commercially available by Xetex, Inc., of Belmont, Californai. It is called Scintaflex and uses a 1/8" x 1" lithium enriched glass scintillator detector, a suitable mount for collimators, and a strip chart recorder for reading display. The object is moved systematically through the narrow beam to perform the neutron gauging and the readout is, of course, instantaneous.

V. Chameton at the Laboratories D'Electronique et de Physique Applique in France is studying the use of microchannel image intensifiers for neutron radiography. One of the papers at the seventh international NDT meeting was on that subject.

Neutron gauging work by the Aerotest, Inc. Group, San Ramon, California, might be mentioned at this stage. A paper entitled "Precision Gauging with a Fluctuating Neutron Source," by Ivan Lamb and Paul Underhill appears in the program of the 1974 Spring Conference of the ASNT.

Image Enhancement

A special group of six papers on methods of image enhancement was held at the Spring 1972 Conference of the American Society for Nondestructive Testing. Different concepts were presented by D.H. Janney et al. of Los Alamos Scientific Laboratory, New Mexico (General Survey); W.L. Shelton of Wright Patterson Air Force Base, Ohio (inc luding impregnation technique); P.W. Hesse and E.L. Criscuolo, Naval Ordnance Laboratory , White Oak, Silver Spring, Maryland (Fourier transform enhancement using optical methods); B.R. Hunt et al., Los Alamos Scientific Laboratory, New Mexico (Enhancement using a digital computer), Karl Lohse, NDE Unlimited, Costa Mesa, California (photographic methods) and Alex Vary, NASA Lewis Research Center, Clevelend, Ohio (television camera and display with analog computer enhancement). Papers have been published in Materials Evaluation as follows: D.H. Janney et al., Vol. 30, No. 9, p. 195 (1972); B.R. Hunt, et al., Vol. 31, No. 1, p. 1 (1973); Alex Vary, Vol. 30, No. 12, p. 259 (1972); and see also Alex Vary and K.J. Bowles, "Application of Electronic Image Analyzer to Dimensional Measurements for Neutron Radiographs, Vol. 32, No. 1, p. 7 (1974).

Image Quality Indicators

Several different approaches for determination of neutron radiograph image quality have been pursued.

One that has been used quite widely over the past three years is "The Visual Image Quality Indicator VISQI) for Neutron Radiography." A complete report on the design and use of this IQI has been published (J.P. Barton, Journal of Materials, Vol. 7, No. 1, p. 18-24, 1972). As its name implies, this IQI is primarily a visual test and is therefore intended for comparative purposes only. A complementary image quality indicator designed for occasional use to give quantitative measurements of a system's characteristics has been described in the publication, "A Method for Comparison of Neutron Radiography Systems," J.P. Barton and M.F. Klozar, Materials Evaluation, Vol. 31, No. 9, p. 169, 1973.

A more sophisticated approach to neutron radiograph image quality control has been published by R.H. Bossi, J.L. Cason and C.N. Jackson, Jr., "The Modulation Transfer Function and Effective Focal Spot as Related to Neutron Radiography," Materials Evaluation, Vol. 30, No. 5, p. 103 (1972).

Another method has been developed by A.A. Harms and colleagues at McMaster University. A simple microdensitometer scan is taken across a "knife-edge" image and the Lorentzian function is used to express the image quality in a single parameter. Development of this work is reported in the following four publications: (1) A. A. Harms, B. K. Garside and P. S. W. Chan, "The Edge Spread Function in Neutron Radiography," J. Appl. Phys., 43, 3863 (1972), (2) A. A. Harms and T. G. Blake, "Densitometer Beam Effects in High Resolution Neutron Radiography," Trans. Am. Nucl. Soc. 15, 710 (1972), (3) A. A. Harms, B. K. Garside and W. T. Hancox, "A Framework for Radiographic and Fluidic Neutron Transmission Analysis," Trans. Am. Nuc. Soc., Vol. 15, Supplement 1, p 14-15, Feb. 1972, and (4) A. A. Harms, "Recent Theoretical-Experimental Correlations in Neutron Radiography," to be published in proceedings of British Nuclear Energy Society Conference on Neutron Radiography, Birmingham, Sept. 1973.

Atomics International has performed for the NASA an extensive study of neutron radiography and the reports entitled "Application of Neutron Radiography Technology for S-11 Quality Assurance" have been published in four volumes--SD-71-270 (1-4). The first volume is devoted to methods of image quality control and describes methods similar to the VISQI and complementary system IQI referenced above.

Work on the ASTM standard method for neutron radiographic image quality is reported in detail elsewhere in this newsletter. At the recent meeting of ASTM (January 1974) two neutron radiographers were present--J. J. Haskins of General Electric, and O. R. Hillig of Atomics International.

The following decisions were taken at that meeting: (1) The proposed neutron radiography standard will be submitted for vote through the x ray radiography committee (under which the neutron radiography project was initially set up). That vote should be completed by June 1974. (2) A new neutron radiography committee will be set up with equal status to the x-ray committee and other NDT methods committees. Thus, in future, neutron radiographers will come directly under the E-7 executive officers for nondestructive testing, rather than under the x-ray committee as before. (3) A main future project for the neutron radiography committee will be the development of an ASTM "Recommended Practice."

The first chairman of this new ASTM committee will be J. J. Haskins of General Electric Co., Vallecitos Center, P. O. Box 846, Pleasanton, California 94560. Correspondence concerning general ASTM standards work for NR should be addressed to Mr. Haskins. Correspondence on the specific project to be developed on ASTM "Recommended Practice for NR" should be addressed to the leader for that project, Mr. H. Berger, Institute for Materials Research, National Bureau of Standards, Washington, DC 20234. Ideas or discussion on methods to incorporate an appropriate resolution test into the ASTM IQI should be sent to Dr. J. P. Barton, Radiation Center, Oregon State University, Corvallis, Oregon 97331.

Reactors for Neutron Radiography

General Atomic, at San Diego, has described a new version of their TRIGA reactor systems that should be especially useful for neutron radiography. Its aims are simplicity of physical construction, low cost, and inherent safety through the characteristic prompt negative temperature coefficient of reactivity. The core consists of 18 Zr-H-U fuel elements containing 93% enriched uranium (standard TRIGA is about 80 elements with 20% enrichment). Active core dimensions are about 7 inches diameter by 15 inches high. The reflector is graphite, and at a power of 250 KW the peak flux in reflector interface is quoted as 9.0 x 10^{12}n/cm^2-sec.

Atomics International, at Canoga Park, California, continue to have available their L-88 reactor design for neutron radiography. A full description of this homogeneous solution 10 KW reactor is available in a paper by J. O. Henrie published in Isotopes and Radiation Technology, Vol. 9, No. 1, p. 41-44 (1971).

The reactor for neutron radiography designed by the French Commissariat A L'Energie Atomique at the center for criticality studies, Valduc, has been professionally described in a paper by M. Houelle published in Supplement Au Bulletin D'Information A.T.E.N., No. 90, July-August, 1971. The report contains six figures on design and operation of the reactor, and four figures showing neutron radiographs taken with the reactors.

Note that the above mentioned French language publication contains a total of five papers on neutron radiography activity in France: The other papers are by J. L. Boutaine (Saclay), A. Settipani (Societe Qualitest), P. Candes (C.E.A. Fontenay-Aux-Roses), M. Vu Hong and G. Breynat (C.E.N. Grenoble). The subjects covered in these four papers are respectively: general principle, industrial applications, safety aspects, and accelerator source techniques.

Reactor Facilities for NR

Examples are given of recent reports on reactor neutron radiography facilities. A 46-page report entitled, "Neutron Radiography at Sandia Laboratories," has been prepared by R. H. Yoshimura and H. D. Moody at Sandia Laboratories, Albuquerque. The report number is SC-DR-710178. It contains preliminary information on both the Annular Core Pulsed Reactor and a Californium-252 system in use for NR work.

A paper entitled, "A High Resolution Thermal Neutron Radiography Facility," by D. M. Alger and S. R. Bull was published in Nuclear Technology, Vol. 17, p. 189-192, February 1973. It presents design and performance characteristics of the facility on the 5 MW University of Missouri Research Reactor.

The paper, "Nondestructive Testing by Neutron Radiography at a Small Nuclear Reactor," by F. Levai in the proceedings of the 7th International NDT Conference 1973 provides a general description of neutron radiography and some characteristics of the University of Budapest facility in Hungary.

Two papers on neutron radiography are included in the proceedings of the December 1971 conference on "Research Reactor Utilization," held in Santiago, Chile. The proceedings have now been published by the International Atomic Energy Agency, Vienna, report IAEA-146. The papers are by J. P. Barton (USA), pp. 355-376 and by R. S. Matfield (UK), pp 377-408.

Four papers on reactor neutron radiography were presented at the ANS National Topical Conference on "Research Reactor Utilization," held at Texas A&M University, February 1972. Summaries are published in ANS transactions, Supplement No. 1 to Volume 15.

The authors are J. P. Barton (Oregon State U.), G. Thomas et al. (U of Missouri), R. L. Tomlinson (Aerotest Ops), and A. A. Harms et al. (McMaster U).

Another national ANS meeting in the series entitled, "Conference on Research, Test and Training Reactors," will be held August 12-14, 1974 in Charlottesville, Virginia. However, this program will not include any special emphasis on neutron radiography. For details see Nuclear News.

Accelerator Source Facilities

L. Vu Hong of C.E.N. Grenoble, France has published a thesis on studies to develop accelerator based neutron radiography. A revue, "Low Voltage Particle Accelerators for Neutron Generation," by L. Holland and M. R. Hawksworth, published in Nondestructive Testing, October 1971, pp. 330-337, is aimed particularly at neutron radiography purposes.

Sealed tube neutron generators are the subject of neutron radiography facility descriptions by A. R. Spowart in Nuclear Instruments and Methods 92 (1971), pp. 613-617 and by D. G. Vasilik and R. L. Murri in Materials Evaluation 29, No. 6, p. 130 (1971). These facilities have been built at UKAEA Dounraey, Scotland, primarily for reactor fuel inspection, and at Dow Chemical Company, Rocky Flats, Colorado, USA, primarily for ordnance examination.

Facilities based on Van De Graaff machines have been described by L. E. Wilson et al. in Materials Evaluation 29, No. 4, p. 69 (1971) and by J. Cassiday (Amarillo, Texas) and Bill Dance (Dallas, Texas) at the ANS, November 1973 meeting--see earlier section of this newsletter. The paper, "Advanced Radiographic Imaging Techniques," by J. B. Beal and R. L. Brown, Materials, Evaluation 31, No. 7, p. 133, 1973 is also concerned with a neutron radiography Van de Graaff facility.

Workers in Germany including P. Jost at Bundesanstaldt Fur Materialprifung (BAM), Berlin, have expressed interest in setting up an NR facility based on a linear accelerator. Previous work reported on linear accelerators includes that by C. A. Hunt, in British Journal of Nondestructive Testing, December 1969 and by W. L. Whittemore in Trans. Am. Nuc. Soc. 12, p. 403, December 1969.

Isotopic Source NR

The following papers concerning neutron radiography were presented at the ANS National Topical Meeting Applications of Californium-252 held at the University of Texas, September, 1972.

"Radiography Using Cf-252" by J. Ray of Battelle Memorial Institute, Columbus, Ohio.

"Cf-252 Neutron Radiography at Battelle-Northwest" by K. L. Swinth of Battelle-Northwest.

"Radiography with the Fission Neutrons from Californium-252" by J. J. Antal and R. L. Becker. Work at the AMMRC, Watertown, Massachusetts.

"Application of Cf-252 for Neutron Radiography of Munitions Items" by E. G. Barnes of Picatinney Arsenal.

"A Radiography and Capture Gamma Ray Facility for Californium-252" by G. D. Atkinson, et al., University of Texas.

"A Cf-252 Neutron Multiplier for Neutron Radiography and Activation Analysis" by L. G. Miller and J. F. Kunze of Aerojet Nuclear Co., Idaho Falls.

Several papers at the Birmingham and San Francisco meetings, listed earlier, refer to progress with isotopic sources. Note that the paper on real time imaging by J. J. Haskins described the use of an ^{241}Am - ^{242}Cm - Be source for neutron radiography. Papers published on isotopic source neutron radiography since the last newsletter include:

"Experiments with ^{241}Am - ^{242}Cm - Be for Nuetron Radiography" by J.P. Barton and M.F. Klozar. Materials Evaluation 30., No. 11, p. 230, 1972. "Developments in Use of Californium-252 for Neutron Radiography" by J.P. Barton. Nuclear Technology 15, p. 56-67, July, 1972.

Progress reports from several centers are published periodically in "Californium-252 Progress" obtainable from the USAEC, P.O. Box A, Aiken, South Carolina. The recent edition (No. 16, December, 1973) includes reports from Intelcom Rad. Tech. on development of an optimized neutron radiography system and from General Dynamics and Advanced Technology Center, Inc., both on applications in the aerospace industry. More routine application work usinq a Cf-252 NR facility is reported by Mound Laboratory in Ohio. Also note Report 4629 issued March 1974 by Picatinny Arsenal, Dover, New Jersey.

A series of meetings on Californium-252 utilization have been sponsored by the USAEC. In March, 1973, the meeting was held in New York City, and there were seven speakers reporting neutron radiography applications with Cf-252. In April, 1974, another meeting in the series was held at San Diego, California. In this meeting, the neutron radiography focus was on applications of Cf-252 in the aerospace industry. Speakers were W.E. Dungan, General Dynamics; J. John, Intelcom Rad. Tech.; M.J. Devine, Naval Air Development Center; A.J. Koury, Naval Air Systems Command; W.E. Dance, Advanced Technology Center; B.W. Boisvert, Kelly Air Force Base; and B.G. Brownlee, Lockheed Space and Missiles.

Flux Boosters

Subcritical assemblies could, in principle, be used with either isotopic or accelerator neutron sources to increase the available peak thermal neutron flux. For different values of K (the chain reaction effective multiplication factor) less than unity, the neutron multiplication varies as 1/1-K. Thus as K approaches unity (e.g., from 0.9 to 0.99), the multiplication increases rapidly, and this must be traded against the increasing difficulty of ensuring that the assembly can, in no circumstances, become accidentally critical. Proponents claim that inexpensive and completely safe systems can be designed with control and licensing problems significantly less than for a critical reactor. Characteristics vary but a typical approach might be to sepnd $10,000 on a small Cf-252 source and $40,000 on the booster to obtain a flux boost of a factor of 30.

Work at the University of Texas has been reported by G.D. Bouchey and S.F. Gage in a paper, "Neutron Radiography Using a Small Subcritical Reactor," published in the journal Nondestructive Testing (see also Trans. Am. Nuc. Soc. 14, 123, 1971).

Two different subcritical boosters have been used at Aerojet Nuclear Company, Idaho. One, designed for irradiation purposes, has a large (10 liter) flux trap region and with the 3 mg Cf-252 source operates at a total power of 100 watts. The second, used for neutron radiography, provides a high resolution beam of L/D 250 with a collimated flux of 5×10^5 n/cm^2 sec. Reports by L.G. Miller, et al. are available in Trans. Am. Nuc. Soc. 14, p. 517, 1971, and in "Californium-252 Progress."

A subcritical booster has also been developed (primarily for neutron activation analysis work) by R.W. Perkins and others at Battelle Northwest Laboratories. A commercially available subcritical booster has been made avialable by Intelcom Rad. Tech. The fuel is aluminum clad uranium-aluminum alloy plates containing enriched (93.4$^{0/0}$) uranium. In the center is a flux trap of high density polyethylene. The designed value of K is 0.990, the thermal flux is boosted by a factor 33, collimated flux for L/D of 20 is quoted at 10^5 n/cm^2 sec.

Miscellaneous Applications

Neutron radiography techniques for application to various metallurgical problems has been developed in several laboratories. In Italy, G. Gasparrini, M. Mangialajo, et al. of the CISE Laboratory in Milan have reported their work in an internal paper, "Applications of NR to studies of Hg_{1-x} Cd_x Te alloys. A more general paper by M. Mangialajo on "Industrial uses of neutron radiography at CISE" was published in the proceedings of the 18th Nuclear Congress of Rome, Roma-Eur, 26-27 March 1973.

The work in Finland by H. Reijonen and J. Forster on NR studies of unidirectionally solidifying Sn-Cd alloys has been published in Metallurgical Transactions, Vol. 2, July, 1971, pp. 1921-1924, and another paper by the same authors appears in Journal of Crystal Growth 12, 1972, pp. 61-62. A more detailed paper, "Neutron Radiography of Unidirectionally Binary Melts with Natural Convection by H. Reijonen will be published in Physica Fennica.

A paper entitled "Localization of boron constituents in steels by neutron irradiation and autoradiography" by J. L. Boutaine and A. Lemonnier has been issued by the C.E.N. Saclay in France, reference TAAR-AR-S-72-06.

An example of metallurgical work in the USA is given by the zero gravity metallurgical experiments carried out as part of the NASA spece program. Some of these were studied by Dr. W. C. Whittemore and colleagues using neutron radiographic techniques at General Atomic, San Diego. Note also "Applications of Neutron Radiography to Vapor Transport Fuel pins" by C. D. Lanzo, D. C. Winterich and L. A. Thaler, Transactions Am. Nuc. Soc., Vol. 15, p. 141, July, 1972, "Neutron Radiography as a Diagnostic Tool in the Study of Corrosion in Lithium-Filled Heat Pipes" by Forman and L. S. Thaler, Materials Evaluation, Vol. 31, No. 2, 1972, p. 25, and "Neutron Radiography Feasibility Studies for Steel Examination for the Liquid Metal Fast Breeder Reactor Program" by K. G. Golliher, USAEC Liquid Metal Engineering Center, Atomics International Report LMEC-71-2. Also, in the MIT Department of Nuclear Engineering, J. M. Edgar has written a master's degree thesis entitled "Nondestructive Testing of High Strength Welds by Neutron Radiography."

Some other miscellaneous applications reports that should be noted include: "The detection of Hydrogen in Cellulose Acetate by NR" authored by R. S. Matfield, Report AERE 6700 from Harwell, England. "Determination by NR of the Thickness of the Carbonated Layer of Concrete Based Upon Changes in Water Content" by H. Reijonen and S. E. Pihlajauaara, published by Cement and Concrete Research, Vol. 2, pp. 607-615, 1972. "Determination by Neutron Radiography of the Location of Polymeric Resins Injected in Rock Fixtures" by R. V. Submramanian and D. Burkhart, published in Nuclear Technology, Vol. 17, February, 1973, pp. 184-188.

The last neutron radiography newsletter was issued just before the fall, 1971 major gathering of neutron radiographers in Miami, Florida. At that meeting, 28 papers were presented on neutron radiography including some on materials applications. Note in Trans. Am. Nuc. Soc. 14, No. 2. the papers "Nondestructive Testing of Brazed joints Using Neutron Radiography" by H. D. Kosanke. The paper presented personally by H. Reijonen and P. Jauho of Helsinki University, Finland, at the Miami meeting, "Observation of Carburetor Icing Using Neutron Radiography" has since been published in full in Materials Evaluation, Vol. 30, June, 1972.

Other application areas include inspection of pyrotechnical devices. Papers in this area are "Doping Explosive Materials for Neutron Enhancement" by H. G. Golliher presented at the 7th Symposium on Explosives and Pyrotechnics, September 8-9, 1971, and "Motion Neutron Radiography at 10,000 Frames Per Second" by J. P. Barton, R. H. Bossi and A. H. Robinson, presented at the 1973 Spring Conference of the American Society for Nondestructive Testing. The abstract is published in Materials Evaluation, February, 1973, p. 34A, and a preliminary review of the work is published in Ordinance, Vol. 58, No. 319, July, 1973.

In the area of biomedical neutron radiography, note the paper "Comparison of X-ray and Neutron Radiography of Pathological Bone Samples" by H. Reijonen, M. Kormano and K. Reijonen issued by the Technical Research Centre of Finland, Electrical and Nuclear Technology Publication 2, Helsinki, 1973, to be published in Investigative Radiology. Also note that the paper "Neutron Radiography of Osseous Tumors" by P. J. Boyne and W. L. Whittemore in Oral. Surg. Oral. Med. Oral. Path. 31 (1971), p. 152 will be followed by further publications on the authors' progress made in use of NR techniques for medical graftings and implants.

Other work on biomedical neutron radiography is in progress at Reed College, Portland, Oregon. Note also the paper, "Neutronography in Medical Research and Pathology" by M. J. Flynn, G. F. Knoll and A. Poznanski of the University of Michigan, CONF-710402, 1, 11-49, Springfield, 1971. At least two centers have reported activity recently in applications of neutron radiography to museum work and archaeology. J.J.M. Robertson of Harwell UK has prepared a report "Neutron Applications to Archaeology" which includes two neutron radiographs, one a study of Roman spearheads and the other a study of Saxon era pottery in which boronated glaze shows up clearly. A report by this same author entitled, "Neutron Radiography in Archaeology," is in preparation. At the November 1973 San Francisco meeting of neutron radiographers, O. R. Hillig of Atomics International described several NR studies of museum pieces carried out in collaboration with Dr. Kearns of the Los Angeles County Museum. Items studied included a Gupta statue from India about 1400 years old, and a delicate Chinese urn about 2500 years old. The neutron radiographs, studied in conjunction with x-radiographs, did provide considerable information on what processes were used to build these objects all those years ago. Also neutron radiography was used to study an Egyptian mummy and a Peruvian mummy. In answer to a question about possible damage to the items, Dr. Hillig noted that insurance premiums of $1000 had been paid to bring the items to the reactor for the neutron radiography.

Finally in this section, comments will be made on three pieces of neutron radiographic technique work.

(1) The cold neutron radiography developments at Birmingham University have shown that thicknesses in excess of 150 mm of steel may be successfully neutron radiographed revealing 2 mm of hydrogeneous material in the center.

(2) The method to provide reduced gamma ray background described by J. R. Shoptaugh and W. L. Whittemore of General Atomic involves the use of a pyrolytic graphite crystal to provide high efficiency diffraction of the neutron beam. Suitable crystal material for a 10 cm diameter beam could be obtained for under $3000. The measurements showed that use of the crystal reduced the neutron intensity by a factor of 50 and the gamma ray intensity by at least 1000, thereby significantly improving the neutron to gamma background ratio.

(3) The work on the detectability of gases using neutron radiography by L. Dahlke at Sandia Laboratory, Livermore, has focussed attention on the gas ^{3}He. It has a very high neutron cross section (5,330 barns), can be obtained at about $100 per liter at standard temperature and pressure, and might be used among other things as a penetrant to reveal cracks in metal structures.

New Addresses

There's a lot of coffee in Brazil, and quite a lot of neutron radiography too. Three former colleagues, Lao Holland and John Rogers from Birmingham and Lac Vu Hong from Grenoble are now all working on neutron radiography projects in Brazil at three different centers. Dr. Holland at the Institute de Energy Atomica, Cite Universitario, Sao Paulo; Dr. Rogers at the Nuclear Engineering Center, Coppe Da UFRJ, Caixa Postal 1191-ZC-00, Rio De Janeiro; and Dr. Vu Hong at Companhia Brasileira De Tecnologia Nuclear Caixa Postal 1941 30,000, Belo Horizonte, Minas Gerais.

News of neutron radiography activity has recently been received from individuals in several other countries: From Romania--Professor Radu Rodica of the Institute for Atomic Physics, P. O. Box 35, Bucharest; from Yugoslavia, Mr. Jeliga Stevovie of the Boris Kidric Institute of Nuclear Sciences, Vinca Belgrad; from Hungary, Dr. S. Juhasz of the Institute of Experimental Physics, Kossuth University, Debrecen; from Spain, N. Alcober, Seccion De Neutrones Lentos, Junta De Energia Nuclear, Madrid 3; from Germany, Doris Ruffner, of the Institut Fur Plasmaforschung, Universitat Stuttgart, 7 Stuttgart 80; and from England, J. F. Walsh, Department of Prosthetic Dentistry, University of Manchester. In Scotland, note that Dr. A. R. Spowart has moved from UKAEA Dounraey (his address at the time of the last newsletter) to the Department of Physics, Paisley College of Technology, Paisley, Renfrewshire. He continues his research on neutron radiography at the Scottish Universities Reactor Centre.

In Iraq, Imad Khadduri of the Reactor Physics Department, Nuclear Research Institute, Tuwaitha, Baghdad is planning to set up a neutron radiography facility on the 2 MW water cooled research reactor.

In the USA, there have been several movements of personnel. First, note that Harold Berger left Argonne National Laboratory in August 1973 and has taken an appointment to work on neutron radiography and allied subjects at the Institute for Materials Research, National Bureau of Standards, Washington, D.C. 20234.

Kenneth L. Swinth spent a year on temporary assignment at the Laboratory of Nuclear Medicine and Radiation Biology, UCLA. He has now returned to Battelle Northwest Laboratory in Richland, Washington.

James A. Morley moved from the Lewis Research Center; his new address is USAEC, Dayton Area Office, P. O. Box 60, Miamisburg, Ohio 45342. Like the people listed above, he plans to continue his direct interest in neutron radiography.

John Cason has left Gamma Industries where he was working with the portable Cf-252 neutron radiography equipment, and has taken a new appointment that is not associated with the field. Donald Garrett, previously with the Los Alamos Laboratory, has joined Gamma Industries as manager of neutron applications, at Baton Rouge, Louisiana.

Howard Aderhold, of the Ward Laboratory, Cornell University, Ithaca, New York 14850, called recently to say he was setting up a neutron radiography facility on the University 100 KW reactor.

At Babcock and Wilcox, P.O. Box 1260, Lynchburg, Virginia 24505, Dr. Holland D. Warren has been concerned with the neutron radiography applications using the 1 MW pool reactor.

At the M.I.T. reactor, Cambridge, Mass. 02139, the names to contact concerning the neutron radiography facility are K. Collins or D.D. Lanning.

A new name a the General Electric Co., Vallecitos Nuclear Center, Pleasanton, California, should be noted: Craig E. Leighty has taken over in the neutron radiography service position previously held by Frank J. Lamphere.

#13. 1974

THE PROPOSED ASTM-IQI

J. P. Barton

COMMITTEE WORKS TOWARDS A RECOMMENDED STANDARD METHOD FOR DETERMINATION OF NEUTRON RADIOGRAPHY IMAGE QUALITY IN U.S. COMMERCIAL NDT

Introduction

In order that a purchase order or other specification can most usefully reference neutron radiography of an item, it is helpful to have a recognized standard method for determination of image quality. For industrial x radiography in the USA, one of the more commonly used methods for determination of image quality is that proposed through the American Society for Testing and Materials (ASTM). A description of the ASTM x-ray penetrameter is available in the ASTM handbook, Part 31, Section E142. Therefore, it is through this society that a committee of neutron radiographers (suppliers and users) has worked over the past three years to develop a proprosed standard method for determination of thermal neutron radiograph image quality. The proposal is now at the stage of formal voting within ASTM.

(a) Summary of Method.

Two types of image quality indicator (IQI) are used. They are to be placed in each and every radiograph no less than 1 inch from the edge of the object being radiographed. The IQI's should be parallel to the film and as close as possible to it. The film should usually be perpendicular to the beam direction.

The first type of IQI is called the "Beam Purity Indicator" and consists of a small block of boron nitride 8mm thick. The block is pierced by three holes one containing a thin (1mm) filter of boron nitride, one containing a similar boron nitride filter backed by a lead filter 2mm thick, and one hole remaining open (see fig. 1). The radiograph is exposed to produce a background film density at the side of the IQI from 2 to 3 density units. Using a diffuse transmission densitometer density, measurements are taken on the radiograph of the IQI at the five positions D_1 to D_5 as indicated in the figure 1. Ratios of these measurements give a measure of the thermal neutron, epithermal neutron, scattered neutron, and low energy gamma content of the image. (See Table 1.)

The second type of IQI is called the Sensitivity Indicator. It is based on the detection of holes through different thicknesses of cast acrylic plastic step wedges (see figure 2). The sensitivity level is determined by the smallest observable hole visible through the stated step thickness.

(b) Numerical Designation of Image Quality.

The proposed ASTM designation of neutron radiographic quality level shall include three components as follows:

NC The thermal neutron content.

$$NC = \frac{D_3 - D_1}{D_3} \times 100$$

(This value to be rounded to the nearest lower number in the series 80,75,70,60,50,40,30.)

S The scattered neutron content.

$$S = \frac{D_5 - D_3}{D_3} \text{ xx } 100$$

(This value to be rounded to the nearest higher figure in the series 5,10,15,20,25,30.)

R The sensitivity level as determined by visibility of holes in the step wedge sensitivity gauge--see Table 2.

(This value to be presented as a digit in the series 1-16.)

EXAMPLE: To specify a radiograph quality with a thermal neutron content of at least 75, a scatter neutron content of not more than 10, and a sensitivity such that a 0.5 mm diameter x 0.5 mm deep hole can be seen through 1.56 mm plastic absorber, the designation is N75-10-6.

Note: The ASTM recommended method proposes that when no designation is specified, radiographs shall meet level N70-15-10.

(c) Additional Notes.

(1) Field Uniformity: The recommended standard method for determining image quality requires that the exposure density over the working area (in the absence of objects) shall not vary by more than 15 percent (±7.5 percent variation in film density from the numerical mean of 5 measurements; one measurement at the center and one 2 inches toward the center from each corner).

(2) Alternative Sensitivity Indicators: In addition to the sensitivity indicator described in figure 2, a series of three other sensitivity indicators have been designed, each of them consisting basically of plastic step wedges of the same dimensions, but containing different types of defect (e.g., grooves, wires, or ridges instead of holes).

(3) Intended Type of Application: Note that the standard method for determining neutron radiographic image quality has been designed primarily with commercial inspection of small dimension ordnance items in mind. For this range of applications, the importance of high beam purity outweighs the need for high beam collimation, and the ASTM numerical designation of image quality is perhaps more a measure of beam purity than collimation. Details in the acrylic plastic step wedges provide a test that is suitably close to the sensitivity of faults in plastic explosive compounds. The document does not claim to be a comprehensive recommended method for use with, for example, inspection problems on reactor fuel elements, or for rather thick objects where geometric resolution becomes dominant.

(4) Recognized Outstanding Needs: The question of a standard method to determine resolution or sharpness of a neutron radiograph will be a future project for the committee.

References

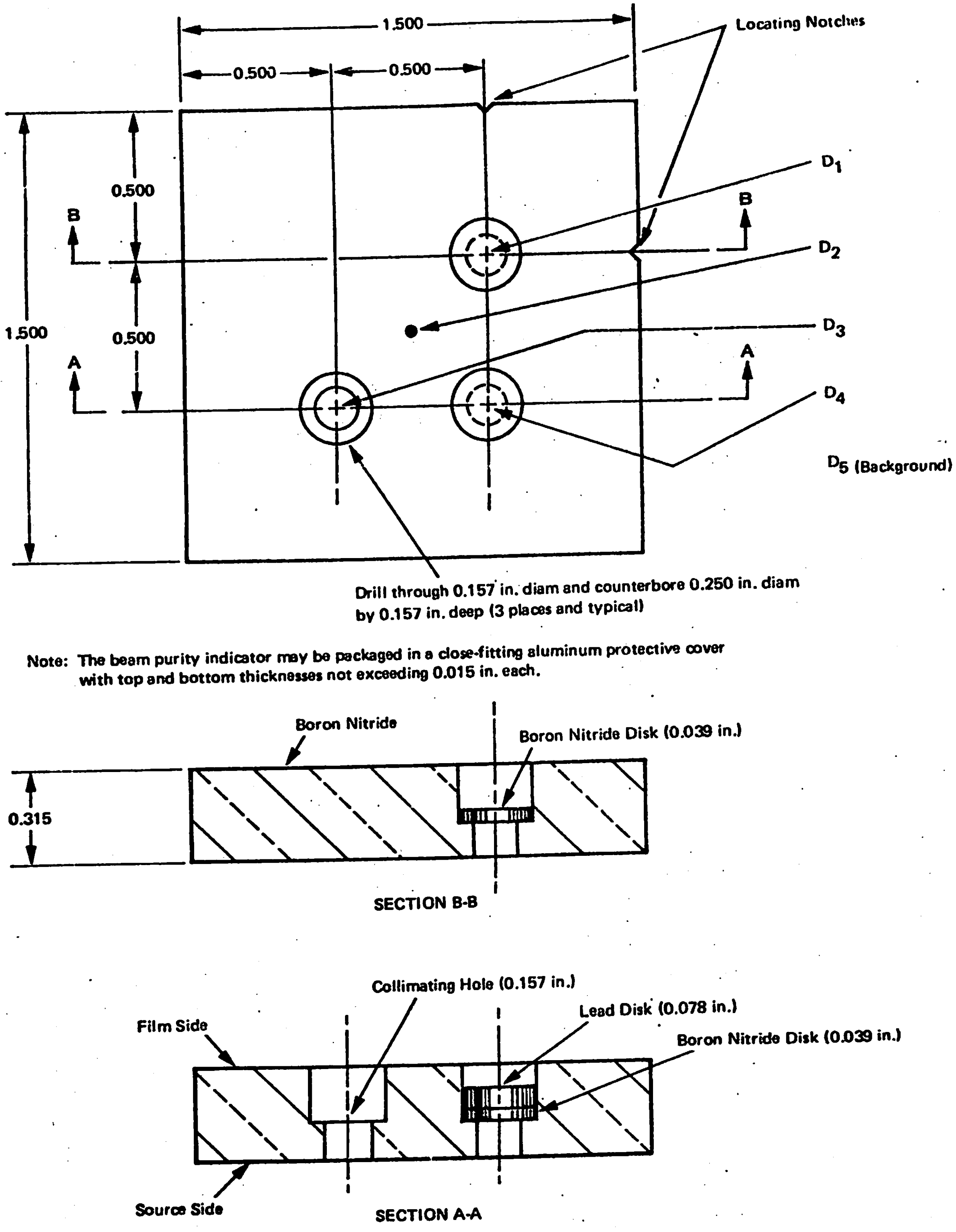
1. "Controlling Quality of Radiographic Testing," Annual Book of ASTM Standards, 1971, Part 31, Section E142.

2. The work of the task group was undertaken primarily by representatives of Aerotest and General Electric (NR Service Suppliers) with Lockheed Missiles and Space Corp. and McCormick-Selph (NR Service Users). Chairman of the task group was J.J. Haskins, G.E. Vallecitos, Nuclear Center, California, USA. Chairman of the ASTM Neutron Radiography sub-committee was E.L. Criscuolo, U.S. Naval Ordnance Lab., White Oak, Silver Spring, Maryland.

Attachments

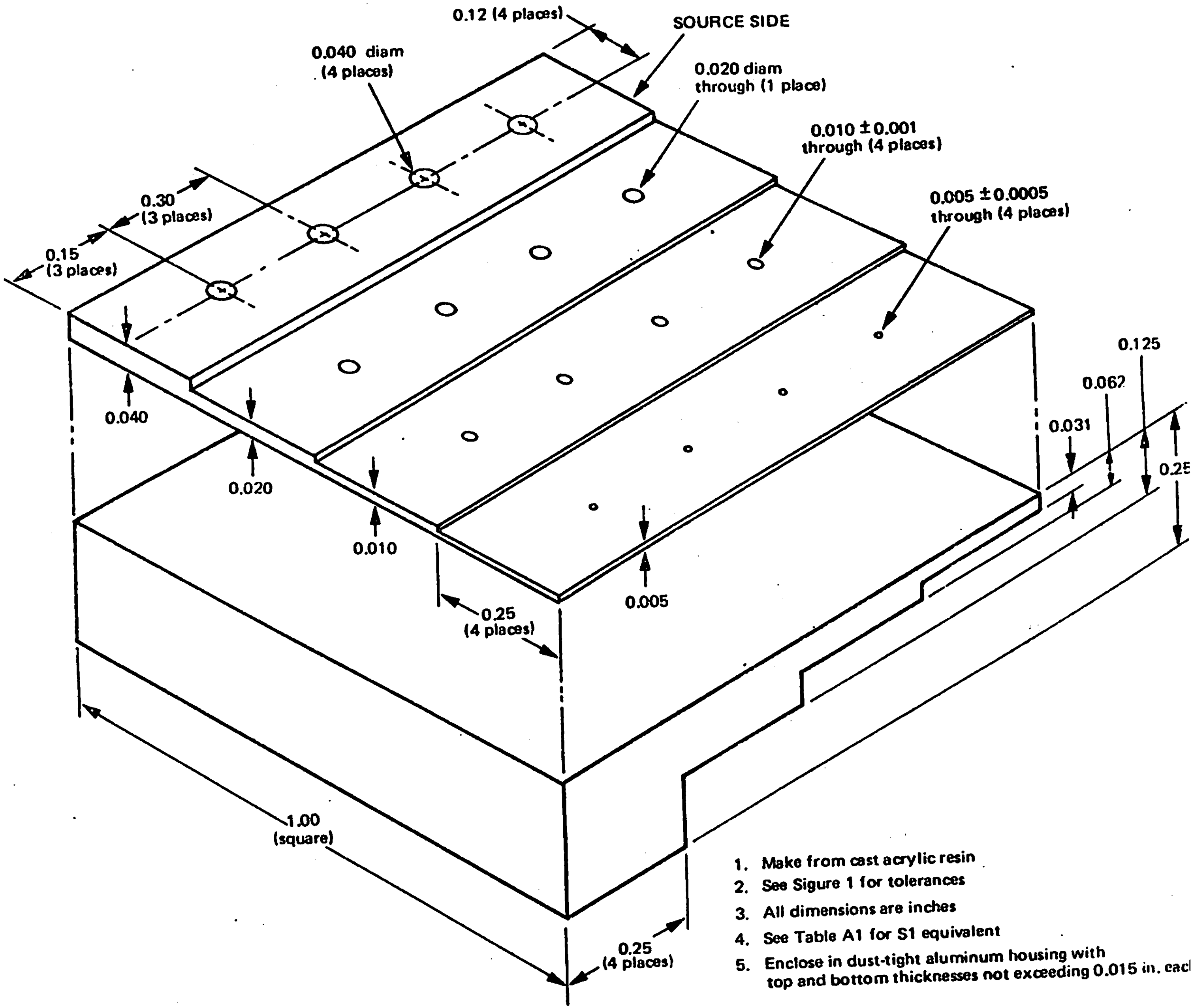
This review of the ASTM proposal includes two figures and two tables.

Figure I —The Beam Purity Indicator (BPI)
Table I —Readings from the BPI
Figure II—The Sensitivity Indicator Type A
Table II—Readings from the Sensitivity Indicator



Note: The beam purity indicator may be packaged in a close-fitting aluminum protective cover with top and bottom thicknesses not exceeding 0.015 in. each.

FIGURE 1. BEAM PURITY INDICATOR (all dimensions in inches)



1. Make from cast acrylic resin
2. See Sigure 1 for tolerances
3. All dimensions are inches
4. See Table A1 for S1 equivalent
5. Enclose in dust-tight aluminum housing with top and bottom thicknesses not exceeding 0.015 in. eac

FIGURE 2. TYPE A SENSITIVITY INDICATOR

TABLE 1

READINGS FROM BEAM PURITY INDICATOR (Figure 1)

Thermal Neutron Content	$\frac{D_3-D_1}{D_3} \times 100$
Scattered Neutron Content	$\frac{D_5-D_1}{D_3} \times 100$
Epithermal Neutron Content	$\frac{D_1-D_2}{D_3} \times 100$
Low Energy Gamma Content	$\frac{D_1-D_4}{D_3} \times 100$

TABLE 2

READINGS FROM SENSITIVITY INDICATOR (Figure 2)

Value of R	Size of Hole Discontinuity		Thickness of Absorber Step	
	mm	Inches	mm	Inches
1	1.0	0.040	0.78	0.031
2	1.0	0.040	1.56	0.062
3	1.0	0.040	3.15	0.125
4	1.0	0.040	6.30	0.250
5	0.5	0.020	0.78	0.031
6	0.5	0.020	1.56	0.062
7	0.5	0.020	3.15	0.125
8	0.5	0.020	6.30	0.250
9	0.25	0.010	0.78	0.031
10	0.25	0.010	1.50	0.062
11	0.25	0.010	3.15	0.125
12	0.25	0.010	6.30	0.250
13	0.127	0.005	0.78	0.031
14	0.127	0.005	1.56	0.062
15	0.127	0.005	3.15	0.125
16	0.127	0.005	6.30	0.250

PERSONNEL QUALIFICATIONS

(Review by J. P. Barton)

COMMITTEE WORKS TOWARDS A RECOMMENDED STANDARD PRACTICE FOR QUALIFICATION OF NEUTRON RADIOGRAPHY PERSONNEL IN U.S. COMMERCIAL NDT

Introduction

In any form of commercial nondestructive testing, it is vitally important that the inspection be performed or approved by completely competent personnel. In radiography, this is true for both the radiographic performance itself and the interpretation of the radiograph. This calls for education, acquisition of necessary experience, and qualification through a proven examination procedure. The importance, and the difficulty, of personnel qualification in radiography was emphasized as recently as August 1973 at the National Topical Meeting held in Portland, Oregon on Radiography in the Nuclear Industry. There were NDT representatives from over 250 companies of the U.S. Nuclear Industry present, and throughout the discussions the point emphasized time and again was the necessity to know and somehow certify that each radiographic inspection has been performed by a fully qualified individual.

In recent years, U.S. government agencies such as NASA and the military agencies have included in their quality assurance manuals requirements for formal procedures to qualify and certify NDT personnel. Typical specifications include NASA NPC 200-1, NASA NPC 200-2, MIL STD 271, NAVSHIP 250-1500 and MIL 1 8950. In many cases, suppliers have been required by various customers to attempt to implement several different qualification and certification procedures. In an effort to reduce the confusion, representatives from many different prime contractors and different sections of the NDT industry got together through the American Society for Nondestructive Testing (ASNT) and have prepared a series of documents known as SNT-TC-1A to provide a standard personnel qualification procedure.[1] The series has several parts (or supplements), one for each of the NDT methods: radiographic, magnetic particle, ultrasonic, liquid penetrant and eddy current testing. An additional part is being prepared for personnel qualification in neutron radiography. During the two years since the commencement of work by this committee,[2] the draft has been widely circulated for comment. Three complete revisions have been performed and circulated. The final draft is now ready for formal vote of approval within the ASNT.

The recommended standard practice sets forth the detailed education, experience, training, methods of examination and method of certification for NDT personnel.

The neutron radiography draft, like the other SNT-TC-1A personnel qualification documents, covers about 40 pages. Listed below are some extracts from the important early sections of the document.

(a) Levels.

The system provides for three levels of qualification:

Level I--An NDT level I individual must have sufficient training and experience to properly perform the necessary tests. He shall be responsible to a person certified to NDT level II or NDT level III for the proper performance of the tests.

Level II--An NDT level II individual shall be qualified to direct and carry out tests in the method. He must also be able to set up and calibrate equipment, read and interpret indications, and evaluate them with reference to applicable codes and specifications. He shall be thoroughly familiar with the scope and limitations of the method, and shall have the ability to apply detailed techniques to products. He shall be able to organize and report nondestructive testing results.

Level III--An NDT level III individual shall be capable of establishing techniques, interpreting specifications and codes, designating the particular test method and techniques to be used, and interpreting the results. He shall be capable of evaluating the results not only in terms of existing codes and specifications, but he also should have sufficient practical background in applicable materials technology to assist in establishing tests and acceptance criteria when none are otherwise available. It is desirable that he have general familiarity with all other commonly used NDT methods. He shall be responsible for conducting examinations of NDT level I and NDT level II personnel.

(b) Examinations.

The system describes four parts to the examination process: Physical, General, Specific, and Practical. For example, the first item under "Physical Examination" reads:

> "An examination to assure natural or corrected near distance acuity such that the applicant is capable of reading J-1 letters on standard Jaeger's test type chart for near vision or equivalent test type. The examination shall be on an annual basis."

The document also includes carefully selected lists of technical examination questions; one set for a level I examination and one set for a level II examination.

(c) Certification.

The system provides rules for certification, and documentation of certification. Examples are:

(1) Certification of all levels of NDT personnel shall be performed by the employer.

(2) At the option of the employer, an outside agency may be engaged to provide NDT level III services. In such instances, the responsibility of certification must be retained by the employer utilizing outside services.

(d) Education and Experience

The system stipulates the required education and experience for each level of qualification. For example, under the heading of level II qualifications one requirement reads:

> "Completion with passing grades of at least two years of engineering and science study at an accredited university, college, or technical institute, plus one year's experience as a certified NDT level I in neutron radiographic testing, plus 30 hours' training in accordance with the training course outlined in Table A-1, level II."

References

1. "Nondestructive Testing Personnel Qualification and Certification," American Society for Nondestructive Testing Recommended Practice, No. SNT-TC-1A (third edition).

2. The work of the task group was undertaken primarily by representatives of Aerotest, Atomics International, General Electric, General Atomic and the University of California at Berkeley. Chairman of the task group was W.L. Whittemore, General Atomic, P.O. Box 608, San Diego, California.

#14. 1976

NEUTRON RADIOGRAPHY, A TECHNICAL REVIEW

Edvard Heiberg Ph.D.
Grefsenveien 5B Oslo 4 Norway

INTRODUCTION

The experiences reported here are from visits to most nuclear centers with neutron radiography programs in Canada, Europe and USA. As indicated in Newsletter Number 13, this included information from conferences attended on both continents. Valuable surveys of the recent status of neutron radiography are available in the proceedings of some of these meetings [1-2], and in published review articles [3-5]. The purpose of this present report is to help answer questions commonly raised during seminars and discussions on both continents.

Neutron Sources

About 70% of the radiography is done at reactor facilities and the remaining 30% is with accelerators and sources. A recent expansion is the use of transportable Cf-252 cameras which have proven their superiority over ultrasonics for detection of corrosion in Navy aircraft as indicated by Dr. J. John [2]. It must, though, be kept in mind that other sources could have have advantages over Cf-252 including factors such as cost, moderation, and half-life.

Reactors in use for commercial neutron radiography can accommodate impressive throughput rates. Last year at Fontenay-aux Roses, 9000 industrial inspections were made at the 6 MW TRITON pool reactor, and this figure is steadily increasing. Another industrial contractor is Aerotest Operations (AO) in California [2]. With existing equipment, they can take up to 300 radiographs in an eight hour day with a 250 kW TRIGA-cored reactor. Recent prices for a 14" x 17" (35 x 43 cm) radiograph varied from $50: - to $150: - depending on quantity and handling requirements.

Divergent Collimators

An example of an advanced but expensive collimator design is that developed for the Oak Ridge Reactor [6]. The lining for the collimator walls was europium, and the L/D ratio was adjustable from 270 to 1000.

A much simpler version is the one at Washington State University

(WSU) with lead shielded input, and the output divergence defined by the aperture and six concentric holes in discs all made of 5% borated polyester [7].

Collimators for reactor facilities are usually custom made. A popular design is the one reported by D. Kedem in Israel with a converging input and diverging output [8-9]. Dr. A. Zeilinger at the "Atominstitut" in Vienna is another specialist regarding low-priced conical collimators.

The variation of flux distributions across image plans can be minimized by aluminum shims [10]. Aperture diameters must normally be larger than 5 mm. At smaller values scattering from the walls can predominate, and it may increase the effective aperture size, although this depends in detail on the construction. RCN in Holland, for example, experienced effects of this kind. Dr. M. Greim at GKSS in Geesthacht reported that a "double" aperture unit with an effective 2 mm diameter input is to be tested on the GENRA-II, 200-cm long divergent collimator. This would provide high resolution radiography with an L/D ratio of 1000. A useful survey about fluxes, beam intensity, collimation and resolution applied by NR has been published by Dr. W.L. Whittemore at General Atomic [11].

A problem with off-centered source cameras is the non-uniformity of the gamma background. Dr. John J. Antal at AMMRC in Watertown and Dr. Bill Dance [2] at the Advanced Technology Center in Dallas use lead shims in their Cf-252 cameras for shadowing the gamma radiation. Captain L.G.I. Bennett at RMC in Ontario has 4 off-centered sources in the camera [1], and these reduce the non-uniformity problem.

Soller Collimators and Anti-Scatter Grids

Inexpensive Soller slit types can be made by stacking slices of boron-painted aluminum on top of each other. In Denmark, a soller collimator has been made using a stack of plastic sipping straws placed in an aluminum frame which fits into a porthole [12]. Honeycomb anti-scatter grids are commercially offered by Research Chemicals in Arizona. At Reed College, the transmission effectiveness of these grids was compared with that of linear ones [13].

Although grid patterns from Soller collimators or anti-scatter grids can be used as fiducial marks, it is often preferred to eliminate them. The anti-scatter grids can be set in motion using a cardoid cam. At Cadarache, the cylindrical tubing containing the Soller tubes was rotated on carefully aligned bearings. R.A. Morris at Los Alamos found that for optical reasons the pattern disappeared at certain distances. An alternative technique adopted in order to minimize the effect of scattered neutrons, is to move the detector back from the object [14].

Object Attenuation

Exact values of the mass attenuation coefficients are needed for the estimation of radiographic sensitivity. Recently, Alan M. Ross of the Fuels and Materials Division at Chalk River Nuclear Laboratories (CRNL) revised the coefficients for thermal neutrons (0.0253 eV), as previous charts contained errors. The revised data is prepared for various isotopes and hydrogen-containing materials. Although the exponential relationship, $I = I_O \cdot e^{-\mu x}$, is not always exactly valid for neutron attenuation, it has been found useful for quantitative evaluations of thicknesses of corroded aluminum [15], and it has been applied for estimating the contrast capabilities of bone, muscle and tissue for neutrons of various energies [16].

Conversion Screens

The two predominant methods for neutron radiography are the direct method using a gadolinium screen or alpha emitter for track etch, and the transfer technique using dysprosium or indium screens.

With a low-intensity beam, quick radiography can be accomplished by a neutron sensitive scintillator. Nuclear Enterprises Inc., (NEI) offers, for example, a camera with a spring loaded cassette for 4.75" x 6-1/2" scintillator imaging, with exposures of $10^4 n/cm^2$-sec for 2 min. The resolution is 0.1 mm [17]. Real time imaging with TV/image-intensifier systems are available [18].

Although valuable data on neutron imaging foils is available [19-20], a recommended approach is to experimentally determine the parameters as done at the CRNL 30 MW NRX pool reactor. A VISQI was employed to measure the resolution at various values of L/D, for various thicknesses of imaging foil [21]. One measurement of resolution was obtained by use of a microdensitometer scan of the edge of the VISQI cadmium strip. On this basis, the optimum combination for their requirements were found to be use of a 2-thou thick Dy foil, and a collimator ratio of 60.

For industrial applications, a commercial 25-μ gadolinium foil is normally employed. CRNL reports the possibility to reduce a 25-micron Gd foil to 5 micron by polishing it through agitation in a powder solution, analogous to polishing a geological specimen. Vapor deposition is, of course, the common method for producing foils of micron thicknesses. However, at the HERALD reactor, they found that resolution did not appear to improve for Gd foils thinner than 100-μ [1].

For transfer imaging, both dysprosium and indium foils have advantages and disadvantages. Indium offers the better resolution, but dysprosium radiographs have the better contrast. Both dysprosium and indium deteriorate with usage. The softness of In results in a poorer ability for intimate film contact, and Dy oxidizes in normal humidity which can degrade the radiographic quality. Dysprosium can be handled after irradiation by hand gloves but indium is too active for such handling.

CRNL tried to combat Dy corrosion by coating a 1/2-thou thick layer of Teflon on a foil, but the result was decreased resolution. K.D. Kok at the now dismantled Battelle Research Reactor reported [2] that the Teflon coating also became brittle and cracked, thus creating a more serious problem than the oxidation itself.

Kok preferred the use of indium foils as they are cheaper and can be obtained more easily in the desired size. Due to the shorter half-life, it could be re-used after a shorter time interval than dysprosium. The major application was imaging of irradiated fuel, and foils covering the entire length of a rod were employed.

For the problem of radiographing curved objects, track etch plastics (discussed later) have a particular advantage over foils. It is difficult to employ flexible cassettes with Gd, Dy or In foils. Indium foils are dimensionally unstable, and dysprosium foils are too brittle to be used in anything but regular flat cassettes.

Most cassettes are made of aluminum, but the more expensive magnesium has been considered as a cassette material because of its low absorption cross section for thermal neutrons. The experience at AO, however, was that even thick aluminum cassettes gave better resolution than the magnesium ones because the scattering cross section for Al is smaller than that for Mg.

Radiographic Films

A great many different types of film are in use by different groups with different requirements in neutron radiography. First, each manufacturer produces a range of films with different characteristics. Secondly, there is significant difference between the characteristics produced by different companies such as Agfa-Gevaert, Dupont, Eastman Kodak, Gaf, Kodak-GB, Kodak Pathé, Ilford, 3M, etc. Thirdly, neutron radiography groups report systematic differences between film characteristics produced by the same company but in different countries. And fourthly, there is, unfortunately, sometimes a difference from batch to batch of the same brand film. Several neutron radiography groups use selected films from more than one manufacturer to meet their particular requirements.

For certain processes, such as gadolinium foil direct exposure imaging, use of single coated film is important to reduce the gamma background. Three methods are reported for eliminating one side of a double sided X-ray film.

1) AO builds "dikes" around the unwanted emulsion area. A bleaching solution poured into the dike, dissolves the flooded emulsion.
2) CRNL covers the unwanted side with tape, and in the fixing bath it disappears when uncovered.
3) At Grumman Aerospace Corporation, they place the unwanted emulsion of a dried and developed radiograph face down on a flat surface. A cotton swab like a "Q-tip" wets the upper surface with caustic soda (NaOH), and care is taken to avoid that no solution drops around the edge to the wanted side. After 5-10 minutes, gentle pressure with the swab should remove the top emulsion. This is followed by a fast rinse under running water to remove both the caustic solution and loosened emulsion. The caustic soda, apparently, breaks down the gelation matrix.

Don Garrett at NBS indicated the possibility to reduce gamma backgrounds by radiographing the object twice. The first exposure includes both neutrons and gammas, and the second only gammas. A subtraction would provide the net result due to neutrons without gammas.

Display of Films

CRNL makes 35-mm slides of radiographs by placing them on a milky glass illuminated from below, and the camera containing a standard color film is mounted above. The developed color film will always display black/white corresponding to black/white in the radiographs.

Track Etch Imaging

A historical review of track etch is found in a recently published book about nuclear tracks in solids

[22]. It all started in 1959 when a Harwell group published the first direct radiographs of electrons causing damage trails in mica. Today, at least 150 dielectrics are known to have track etch capabilities.

But the discovery that plastics such as polycarbonates, cellulose acetates and nitrates also exhibit chemically etched trails, quickly expanded the application into dosimetry [23] and radiography. Fission products like those from ^{235}U were first employed, but now neutron conversion like the (n,α) reactions from ^6Li and ^{10}B are most common. Kodak-Pathé [24] offers the CA 80-15 CN-film for radiography, and the LR-115 for dosimetry. A valuable review of solid state track detectors for neutron image recording has been prepared by Dr. S.A. Durrani and H.A. Khan [1].

G. Farny at Saclay employs now 10 m long and 12 cm wide Kodak-Pathé CA 80-15 cellulose nitrate (CN) rolls for the routine inspection of irradiated fuel [1]. The length is selected so that an entire light water reactor fuel pin can be scanned in a single exposure.

The exposure time is 10 min. and the etching time is 20 min. in 2.7-n KOH at 30°C. Besides offering improved resolution of detail and quicker inspection than the dysprosium or indium transfer foils, track etch competes well for detection of porosities and cracks. It is also easier to etch long sheets of plastics than to develop long film sheets.

An added feature is the possibility for making intermittent prints of various contrast during the etching process. The underetch is best for high neutron transmission areas like spacings between can and nuclear fuels, and the over etch is best for details of the fuel interior. Thus, a single neutron exposure with track etch can be as informative as several different radiographic exposures with other imaging methods.

The inherent resolution of CA 80-15 has been indicated to be superior to that of other imaging methods used for neutron radiography including Gd/SR [25]. Another advantage is the linear response.

High precision dimensional analysis of radiographs is particularly well suited to track etch imaging. The French ORAMA-500 viewer with X50 magnification is recommended for quick estimation of radiographic dimensions. With experience, dimensions can be measured to within 10 microns accuracy.

There are various ways to enhance a track etch image including use of fluorescent dyes and crossed polaroid filters [26]. A superior method, however, is to use an enlarger which simultaneously enhances and magnifies, and an added augmentation is obtained by imaging on Kodalith paper. The etched sheet is placed immediately below the double plano-convex condensor system which focuses the light from the point source onto the image plane passing through the clear unperturbed areas of the plastic sheet. The light hitting the faint tracks is scattered out of the system.

R. Barbalat at Saclay reports that diffuse light offers better enhancement with Kodalith paper than a point source. An explanation may be the difficulty to exactly place a "point" source in the focal spot.

According to Mr. Jean Barbier at Kodak-Pathé, the reproducibility problem with track etch plastics can be serious. The manufacturing conditions have a great influence on the quality of the plastic track detector including the molding or extrusion processes. It is important that the material is brittle and chemically unstable in order to achieve optimum results. Relevant manufacturing conditions include solvent used for the colloidal solution, type of coating machine, coating speed, and moisture content in the drying air.

Some groups such as the Army Materials and Mechanics Research Center have developed their own methods for manufacture of NR track etch plastics.

Radiography and Gaging of Nuclear Fuel

In-house inspection of both unirradiated and irradiated fuel is today a major application of NR. For example, the Westinghouse Hanford Company report an extensive examination by NR of unirradiated mixed oxide fuel pins [2]. And in Ljubljana NR has been applied to irradiated TRIGA fuel to supplement X-radiographic information regarding elongation of elements [27].

Occasionally a neutron gaging technique can be valuable such as for inspection of hydrogen in zircaloy cladding [28], and of reactor control materials such as B_4C density variations in nuclear fuel pins [29].

A unique virtue of thermal NR is the capability to differentiate between the isotopes of hydrogen, cadmium, uranium and plutonium used in reactor technology. It could thus be feasible to measure by microdensitometry the enrichment and burn up of fuel.

At CRNL, a pilot study with a double beam Joyce-Loebl microdensitometer gave the preliminary result that a 4% enrichment of ^{235}U in uranium was measurable within 5% accuracy. At 1% depletion (3% left) after irradiation to 8000 MWd/ton U, the error was 2-300 MWd/ton U. Although the accuracy is sufficient, the method is laborious.

The Japanese report the use of a fluorescent converter, ZnS(Ag) + LiF with Neopan SS film for detection of a 2% enrichment difference in a 83% enriched UO_2 pellet. An improvement could probably be achieved with a high contrast film and a monochromatic beam [30].

A dual beam facility for Dy-transfer radiography of nuclear fuel has been developed at the 2-kW homogenous reactor in Denmark. The two adjacent beams are parallel to each other with image intensities of about $10^5 n/cm^2/s$ and L/D values equal to 100. A rod passes both cameras with one section being exposed for 20 min. at the time.

Dr. D.C. Cutforth at TREAT has used dysprosium foils for thermal NR and indium foils for epithermal imaging. Characteristic neutron exposure times were 6 min. for Dy and 18 min. for In. For the dysprosium transfer GAF-400 film was employed and Kodak AA for indium. Although the TREAT spectrum is relatively soft $(U, Pu)O_2$ fuel has been routinely inspected there with resonance neutrons.

In Finland, a balanced filter technique has been tested for the determination of ^{239}Pu and ^{240}Pu in reactor fuel with a quantitative accuracy of about $1.5 \times 10^{-3} g/cm^2$ [31].

Hydrogen Radiography and Gaging

The capability of neutrons to "see" hydrogen and "moisture" has found many usages, and some of the techniques and applications will be indicated.

The hydrogen sensitive (HYSEN) scattering method as used by GE [32, 33], has also been used by centers such as the Cise laboratories in Italy. It has about the same sensitivity as alternative methods, but it also tells where the hydrogen is located.

Hydriding of faulty regions in zirconium nuclear fuel clad has been studied by radiography [2]. Alternatively, hydrogen concentrations of about 100 ppm can be recorded by a dual BF_3 counter system. CRNL employed a 1/4-inch beam for this, and found that the precision was about equal to that obtainable from the radiographs.

Investigations of yttrium-zircaloy combinations [26], have included the utilization of yttrium as a hydrogen "sink" in zircaloy fuel cans in order to reduce the mechanical failure problem caused by hydrogen embrittlement. Pu-fission and BF_3 counters were used for the gaging.

Hydrogen diffusion into other substances has been extensively studied in Vienna by Professor H. Rauch's group [1]. An unexpected indication was that the H_2O - D_2O diffusion coefficient at 20°C was dependent upon concentration. The studies include diffusion into metals like vanadium, beta-titanium, niobium, tantalum, and also osmosis in plants [34].

At high temperatures hydrogen losses in concrete shielding may cause embrittlement, and the Rauch group has completed an investigation by NR of this problem using thermocouples to measure the temperature gradients. The comparison between thermal neutron and X-radiographs has been for checking the homogeneity of glue layers and inspecting plastic seals [35].

Neutron radiography is being used for detection of subsurface corrosions in aircraft structures by IRT Corporation, and here again it is the hydrogen in the corrosion compounds that is being revealed.

In the inspection of ordnance items, it is again frequently hydrogen that is providing the contrast. A method of significantly improving the capabilities of neutron radiography is to use cold neutrons for providing contrast between hydrogen and metal, and this technique is now in routine use for general application in England. Protons are also sensitive probes for corrosion detection as reported by B.H. Armitage at Harwell.

Hydrogen in corrosion has also made it possible to neutron radiographically provide information about ancient archeological specimens. Neutron radiographic studies of archaeological specimens show that corrosion patterns can be revealed about the ancient forging methods as reported by R.S. Matfield [1] and T.J.M. Robertson [36], A.O. Hillig applied doping materials for enhancement of museum art objects [2].

For certain applications, neutron gaging is more sensitive to hydrogen thicknesses variations than radiography [37], because a counter can more easily discriminate against unwanted background like gammas and fast neutrons [38, 39].

Some of the biomedical applications of NR are based on the discontinuity of hydrogen densities like osseous tumors [2], but neutron imaging in vivo is difficult because the scattering and dose problems are more severe than those for X-rays. Dr. M.V. Davis at Georgia Tech contemplates the use of a gamma-free 1.5 Å neutron beam to investigate hydrogen transport mechanisms such as found in proteins. The 20 barn scattering events will be depicted by an image intensifier system.

High Resolution Radiography

Conventional radiography with large L/D values and track etch have been mentioned as two methods for high resolution radiography. The initial studies in Ljubljana, however, were with a 5-micron Gd foil in front of a Kodak MR emulsion for the microradiography of a 100-micron metallurgical sample. The spatial resolution was better than 8 micron [1]. A high-contrast neutron absorbing medium is the key to success for microstructural investigations, and in Ljubljana the present segregation studies of boron in aluminum and iron are done by alpha autoradiography recorded on LR-115.

Recently CRNL performed a similar experiment on the grain structure of reactor materials like Zr_3AlB in stainless steel. The technique was to press a thin polished slide of Zr_3AlB against a LR-115 film, and then expose it to a neutron beam for about a day. The film was etched for 20 min., and the resulting track etch showed a distinct network-like distribution of boron as if it was located around the perimeter of 100-micron grain sizes. The conclusion was that the boron had been localized within some kind of larger structure common in zirconium-based alloys.

High-resolution alpha autoradiography has also been performed on PuO_2/UO_2 fuel by A.T. Jeffs [40], and another application is that of fingerprinting [41].

Fast and Cold Neutron Radiography

Fast NR has been pursued by AMMRC in Watertown using the fission energy spectrum from Californium-252 which forms a conveniently small point source [42].

Cold neutrons can penetrate thick sections of heavy metals like steel [43], as discussed by Hawkesworth and Walker [1]. With a residual beam from a 5 MW HERALD, they radiographed 1 mm plastic placed between two 7.6 cm thick steel slabs. This H_2O-moderated pool reactor, incidentally, offers the most versatile NR facilities including thermal, epithermal and subthermal beams [1].

Radiography with very cold neutrons (VCN) has potentiality because the absorption cross sections for 10^{-6} eV neutrons are about 150 times greater than those for thermals [44]. The advantage of VCN radiography is that it extends the range of NR to include very thin samples.

Small Source Work

Useful neutron radiography has been done with the neutrons of MeV energy that are directly available from typical D-T or Van De Graaff accelerators [45]. However, the range of contrasts is limited and most centers using small accelerator sources first thermalize the neutrons. These centers include Advanced Technology Center [2], Grumman Aerospace Corporation [2], and Mason & Hanger Corporation in the USA [2]. In Europe, groups like those at Birmingham and Grenoble have been actively engaged in accelerator NR and the Woolwich Arsenal Center has demonstrated use of an accelerator alternately as X-ray or neutron source [46].

In Toronto, work has been done on use of a pulsing mode accelerator for neutron radiography [47].

Neutron multipliers [48] with sources like ^{252}Cf are becoming commercially available for neutron radiography and the Mound Laboratory in Ohio has published a conceptual "In-Line" design for NDE using such a system [2].

Other Advanced Techniques

At Oregon State University, J.P. Barton, R.H. Bossi and A.H. Robinson have developed and applied the technique of high speed neutron radiography [49]. By this means, NR can be used not only to test the integrity of static ordnance devices, but also to study their mode of operation at the instance of trial firing events. For example, neutron radiographs revealing the motion and timing of propellant burn up as viewed through a steel rifle barrel were taken at frame rates of 10,000 frames per second. Single shot stop motion neutron radiography using a fast burst reactor has been reported by C. Aseltine at the Aberdeen Proving Ground, and by M.L. Mullender and V.J. Hart at Aldermaston [50, 1].

Another area of recent development is that of three dimensional neutron radiography. The purpose of this is to enable thick complex objects to be radiographed and usefully interpreted. Such an object is a fast breeder reactor fuel assembly which typically comprises two hundred or more small fuel pins many of them stacked one behind another.

Professor J.P. Barton and colleagues at Oregon State University are working in three dimensional neutron radiography using computerized axial tomography. This is the topic that is revolutionizing the medical radiography field, for example through the EMI brain scanner. A basic difference between the medical approach and the neutron radiography approach is that, whereas point source--point detector systems can be used for X-ray scanning, the neutron process uses a broad beam and broad foil detector to obtain sufficient neutron statistics for indium resonance activation transfer imaging [51]. Professor W.L. Parker, H. Berger, N.P. Labinski and K.T. Reimann, in work performed at the National Bureau of Standards, have worked on another form of three dimensional reconstruction borrowed from medical X-radiography. In this approach, a series of six to ten radiographs are taken at slightly different angles, the transparencies are viewed when stacked one behind the other, and by movement of the films different planes are effectively brought into focus. The method has been demonstrated using thermal neutrons, where, of course, the reactor source has to be kept still and the object and image screen rotated; as opposed to the X-ray method where the source and image screen are moved [52].

Another interesting method of X-ray tomography is the "Tomorex" method developed by Professor C.A. Morris at the University of Texas in San Antonio. The laminography provides curved layer zonographs at preselected levels with minimum peripheral distortion for a typical rotation movement of 240°.

Freznel zone imaging with neutrons has been considered by Professor S. Kaplan at the University of

California at Berkeley using a nonredundant source plate, and by Professor A.M. Jacobs and colleagues at Pennsylvania State University. This appears to be difficult and quite far from the application stage, as yet.

Definitions

Terms that are being frequently used in neutron radiography, and that are usually taken from X-ray terminology include: exposure, film density, radiographic contrast, contrast sensitivity, latitude, speed, and resolution. Of these, the latter concept of "resolution" is one of the more difficult to define. Although information can be extracted from the VISQI, ASTM beam purity indicator (BPI) and sensitivity gages A, B, C, & D, the resolution through, for example, a thick hydrogenous object has still to be based on trial and error. The most satisfying way to define resolution is by the optical analogy with modulation transfer functions (MTF's), thus expressing the final result as line pairs per unit length (lp/mm) [53,54].

A common method to evaluate the inherent resolution of imaging foils like Gd, Dy, In and track etch plastics is the knife-edge technique [20, 55, 56]. Resolution is here defined by cutting the toe and shoulder at say 16%, 84%, or 10% and 90% of maximum height of the S-shaped curve obtained from a microdensitometer scan across the image [57].

Acknowledgements

The list is too long to mention all contributors. A special acknowledgement goes to Dr. M.R. Hawkesworth at the University of Birmingham who clarified various concepts during an eight month stay in England. At the very start of these transatlantic and continental tours, the advice of Harry Berger was gratefully appreciated, and visits to Alan M. Ross in Canada were of great importance for the deeper understanding of nuclear fuel radiography. Dr. W.L. Whittemore generously provided slides for lectures, and Professor John P. Barton provided both assistance and encouragement for the publication of this report. I sincerely thank everybody involved.

References

1. Radiography with Neutrons, BNES 1975, editor: M.R. Hawkesworth; Conference held at the University of Birmingham, 10-11 September 1973.

2. Practical Applications of Neutron Radiography and Gaging, ASTM STP 586, editor: H. Berger; Symposium held at the National Bureau of Standards, Gaithersburg, Md., 10-11 February 1975.

3. Neutron Radiography, H. Berger, Annual Rev. of Nucl. Sc. <u>21</u>, 335-364, 1971.

4. The Present State of Neutron Radiography and its Potential, H. Berger, Mat. Eval. <u>30</u>-3, 55-65, March 1972.

5. Neutron Radiography, A.R. Spowart, J. of Physics E; Sc. Instr. <u>5</u>, 497-510, 1972.

6. Development and Operation of a High-Intensity, High Resolution Neutron Radiography Facility, B.E. Foster, S.D. Snyder, V.A. Carlos and R.W. Clung, ORNL-4738, December 1971.

7. The WSU Neutron Radiography Units, G. Hinman, J. Ogren and

D. Burkhart, The Proc. of the 2nd TRIGA Owner's Conference, 1972.

8. Divergent Beam Collimator for Neutron Radiography, J.P. Barton, Materials Evaluation 9, 45-46, 1967.

9. A Method for Obtaining a Large Area Beam from a Reactor Beam Tube for use in Neutron Radiography, D. Kedem, Proc. of "Irradiation Facilities for Research Reactors", IAEA-SM-165/10, p. 165-172, Vienna 1973.

10. A Method for Obtaining a Homogenous Flux in a Reactor Beam Tube, D. Kedem, M. Mahlav and I. Pelah, NIM 102, 87-89, 1972.

11. Fluxes, Beam Intensity, Collimation and Resolution for Neutron Radiography, W.L. Whittemore, GA-9472, 7 July 1969.

12. A Simple but Inexpensive Collimator for Neutron Radiography, J. Olsen and L. Mortensen, NIM 121, 617-618, 1974.

13. Measurement of Antiscatter Grid Effectiveness in Thermal-Neutron Radiography of Hydrogenous Materials, J.A. Rau and W.L. Parker, Nuclear Technology 16, 458-461, November 1972.

14. Contrast Sensitivity in NR, J.P. Barton, Applied Materials and Research 4, 40-46, 1965.

15. Quantitative Determination of Corrosion Using Neutron Radio-Graphy, J. John (presented at Cf-252 Utilization Meeting, San Diego, Cal., 4-6 November 1975).

16. Neutron Radiography - Principles and Biomedical Applications, A.E. Profio (presented at Laboratory of Nuclear Medicine and Radiation Biology, UCLA, 18 July 1973).

17. Low-Flux Neutron Imaging, K.L Swinth, Brit. J. of Non-Destructive Testing 16, 129-136, Sept. 1974.

18. Evaluation of a Real Time Imaging System for Neutron Radiography, J.J. Haskins, GE-Pleasanton, NEDC-12512, 29 May 1973.

19. Optimization of Detector Parameters in Neutron Radiography, N.D. Tyufyakov, A.S. Shtan and V.S. Yaskevich, Moscow, USSR (presented at VII IC NDT, Warsaw, Poland, 4-8 June 1973).

20. Converter-Thickness for Optimum Intensity in Neutron Radiography, W. Müllner and M. Jex, NIM 103, 229-233, 1972.

21. A Visual Image Quality Indicator (VISQI) for Neutron Radiography, J.P. Barton, Journal of Materials 7, 18-24, 1972.

22. Nuclear Tracks in Solids: Principles and Applications, R.L. Fleischer, P.B. Price and R.M. Walker, U. of California Press, 1975 (605 pp.).

23. Electrochemical Etching Amplication of Low-LET Recoil Particle Tracks in Polymers for Fast Neutron Dosimetry, M. Sohrabi, Ph.D. thesis in the School of Nuclear Engineering, Georgia Institute of Technology, Nov. 1975.

24. Kodak-Pathé, 30 Rue des Vignerons, 94300 Vincennes, France.

25. Über die Innere Unschärfe Einiger Radiographischen und Neutronographischen Prüfverfahren der

Aktiven Brennelemente, M. C̃opič, D. Horvat, R. Ilić, M. Najžer and J. Rant (to be published in Materialprufüng).

26. Two Methods to Increase the Contrast of Track-Etch Neutron Radiography, J. Morley, NASA TM X-67947 (1972).

27. Experience with TRIGA Aluminum-Clad Fuel Elements, M. C̃opič, V. Dimic, R. Ilić, L. Lipić and J. Rant; Third European Conference of TRIGA Reactor Users, München/Neuherberg, 29-31 October 1974.

28. On the Isothermal Hydrogen Diffusion in Zircaloy-Yttrium-Combinations (GKSS 73/E/3), F. Frisius, H.-J. Lahann, H. Mertins, W. Spalthoff and P. Wille, Berichte der Bunsen-Besellschaft für physikalische Chemie <u>76</u>-12, 1216-1220, 1972.

29. Neutron Gauging of Reactor Control Materials, H. Toffer (presented at Cf-252 Utilization Meeting, San Diego, Cal., 4-6 Nov. 1975).

30. Neutron Radiography Experiments at JRR-4 (I), K. Tomii, G. Matsumoto, O. Sato, K. Takagi and I. Hattori, J. of Nuclear Sci. and Tech. (Tokyo) <u>11</u>-4, 153-167, 1974.

31. On the Determination of ^{239}Pu and ^{240}Pu from Reactor Fuel by Neutron Radiography with Filtered Neutron Beams, H. Reijonen and P. Jauho, TRCF, Electrical and Nuclear Technology Publication 4 (1973).

32. Neutron Radiographic Detection of Metallic Hydride, H.D. Kosanke (presented at Symposium "Hydrogen in Metals - Effects on Properties, Selection and Design", Joint ASM-Processing Research Institute of Carnegie-Mellon University, Penn., September 1973).

33. Hydrogen Sensitive Scattering, H.D. Kosanke, TANSAO <u>14</u>-2, 533, 1971.

34. Experimental Diffusion Measurement of Light and Heavy Water Mining Using Neutron Radiography, A. Zeilinger, M. Suleiman and H. Rauch (to be published in Atomkern Enerie).

35. Moisture Transport in Concrete of the SNR-300 Investigated by Neutron Transmission. A. Zeilinger and R. Hubner, Kerntechnik <u>18</u>-3, 119-125, 1976.

36. The Development, Operational Experience, and Present Position of Neutron Radiography in the U.K.A.E.A., T.J.M. Robertson, Euratom IDWG (74)/P3.1 (1974).

37. Neutron Radiography Newsletter, May 1973, Aerotest Operations, 3455 Fostoria Way, San Ramon, Calif. 94583.

38. Precision Gaging using a Reactor as a Neutron Source, I. Lamb and D.E. Underhill (presented at ASNT Spring Conference, Los Angeles, Calif., 11-14 March 1974).

39. Ein Neutronenflussdichte-Integrator für des Projekt FR2/108, H. Schülken (KFZK den 10.5.74), Karlsruhe 1974.

40. Improved Resolution in Alpha Autoradiography, A.T. Jeffs, Nucl. Appl. <u>5</u>, 91-93, Aug. 1968 (AECL-3128).

41. Reproduzierung von Fingerabdrücken durch Autoradiographie (GKSS 74/I/41), L. Greim and H. Lange (1974).

42. Radiography with the Fission Neutrons from Californium-252 , J.I. Amtal and R.L. Becker, ERDA Conf. 720902 (1972).

43. Radiography Examination Through Steel using Cold Neutrons, J.P. Barton, Brit. J. of Applied Physics 16, 1833-1834, 1965.

44. Neutron Radiography with Very Cold Neutrons, J.C. Bates and S. Roy, NIM 120, 369-370, 1974.

45. Fast Neutron Defectoscopy Development, V.I. Gorbunov and G.Sh. Pekarskii, Tomsk, USSR (presented at VII IC NDT, Warsaw, Poland, 4-8 June 1973).

46. Neutron Radiography with a 5.5 MeV Linear Accelerator and Beryllium Source. C.A. Hunt, Brit. J. of NDT, 11, 78-85, 1969.

47. Novel Techniques in Neutron Radiography with a 35 MeV Linear Electron Accelerator, J.S. Hewitt, M.K. Aydogdu, G.R. Blumenauer and H.A. Robitaille, Nondestructive Testing (GB) 7, 315-322, Dec. 1974.

48. Source Multiplication Studies using a Californium-252 Source, Brent Wei-Teh Lee, Ph.D. thesis, November 1975, The Pennsylvania State University, Department of Nuclear Engineering.

49. High Speed Motion Neutron Radiography, A.H. Robinson and J.P. Barton, Trans. Am. Nuc. Soc. 15 140, 1972.

50. Time Resolved Neutron Radiography Using a Fast Pulse Reactor, C.L. Aseltine, R.D. Strich, Nuc. Tech. 20, 107-114, 1975.

51. Neutron Radiography for Nuclear Fuel Assemblies, J.P. Barton (presented at VIII IC NDT, Cannes, France, 6-11 September 1976).

52. Three-Dimensional Inspection by Thermal Neutron Laminography, H. Berger, W.L. Parker, N.P. Lapinski and K.J. Reimann (presented at ANS 1976 Annual Meeting, Toronto, Canada, 13-18 June 1976).

53. Measurement of Modulation Transfer Functions of Neutron Radiographic Systems, D.M. Alger and S.R. Bull, TANSAO 22, 145-146, 1975.

54. The Fourier Integral and Its Applications, A. Papoulis, McGraw-Hill, New York, 1962.

55. Review: Radiography with Neutrons, M.R. Hawkesworth and J. Walker, J. of Mat. Sci. 4, 817-835, 1969.

56. The Factors Involved in an Assessment of Radiographic Definition, R. Halmshaw, The J. of Photographic Science 3, 161-168, 1955.

57. Measurement and Calculation of Unsharpness Combinations in X-Ray Photography, H.A. Klasens, Philips Research Reports, 1-4, 241-249.

#15. 1977.

ACTIVITIES IN NR AT RISO, DENMARK

J.C. Domanus
Nuclear Department
Elsinor Shipbuilding & Engineering Co., Ltd.
Dk-3000 Helsingor, Denmark

1. INTRODUCTION

Routine neutron radiography was started late in 1975 and since then about 1500 neutron radiographs were taken. The DR1 reactor was adapted for NR of irradiated fuel rods. Many of the fuel rods to be examined are fabricated at Riso and are irradiated in the 10 MW DR3 reactor. After irradiation, the rods are first transported to the Riso Hot Cells, where the fuel elements are disassembled and are subjected to different nondestructive examinations. Other fuel elements arriving at Riso for post irradiation examination are first disassembled in the Hot Cells. There the individual rods are loaded into the transport container and sent to the DR1. Rods varying in length from 170 mm to full-size power reactor rods up to 3 m long have been neutron radiographed.

2. THE DR1 REACTOR AS NEUTRON SOURCE

The DR1 reactor is a small (2 kw) uranyl sulphate solution reactor designed by Atomics International, U.S.A. It provides a maximum thermal neutron flux of 6 x 10^{10}n/cm^2-sec, and a fast flux of 12 x 10^{10}n/cm^2-sec

3. THE DOUBLE BEAM NEUTRON RADIOGRAPHY FACILITY

The Riso double beam neutron radiography facility is schematically shown on Figure 1. Two graphite blocks (3) have been removed from the reflector (1), thus permitting the neutrons from the reactor core (2) to emerge through the reactor shielding as two beams.

The neutron flux reaching the object to be radiographed has an intensity of 1.8 x 10^6n/cm^2-sec at the left port and 1.4 x 10^6n/cm^2-sec at the right port.

The irradiated nuclear fuel rods are transported from the Hot Cells to the DR1 reactor in a dual-purpose transport/exposure container (5). At the back of this container a steel rod (6) is attached, by the use of which the rod (8) can be pushed out of the container and positioned in the two neutron ports. This part of the rod which has left the shielding container (5), enters a shielded enclosure made of concrete.(7) The imaging foil is introduced behind the fuel rod to be radiographed by means of the mechanism (9) consisting of two curved guides, which accommodate the foil.

The neutron beam, originating at the reactor core (2), is collimated in the graphite collimator, having an inlet of 2 cm (vertically) x 8 cm (horizontally), and an outlet of 10 x 10 cm. The distance between the inlet and the exposure surface is 220 cm, which gives an L/D ratio of 110 (in the vertical direction).

The cadmium ratio (measured with gold) is 4.2 at the left port ($1.8 \times 10^6 n/cm^2/sec$) and 3.8 at the right port ($1.4 \times 10^6 n/cm^2$-sec).

4. TRANSPORT AND EXPOSURE CONTAINER

For the purpose of transport of fuel elements between the Hot Cells and the DR1 reactor two multi-purpose transport/exposure containers are used. One is designed to accommodate fuel rods up to 2.5 m in length and the other up to 4.5 m.

In the Hot Cells, fuel rods to be neutron radiographed are placed in an aluminum canning tube (wall thickness of 1 mm) which protects the container from contamination and at the same time serves for manipulation of the rods during neutron radiography. A steel rod is fastened to one end of the tube to position the fuel rod in the beam. At the end of the steel rod a square or a hexagonal plate (see 6 in Figure 1) can be affixed. With this plate rotation of the rod is possible.

5. EXPOSURE TECHNIQUE

A 0.1 mm dysprosium activation transfer foil is used (40 x 120 mm). This foil is introduced through the guiding mechanism (9 on Figure 1) to be in close contact with the rod under examination. After the exposure (about 30 min for Agfa-Gevaert Structurix D4 film or 90 min for Kodak single coated SR film) the Dy foil is removed from the exposure mechanism (9) and transported to the darkroom. Here X-ray film is placed at both sides of the foil and the foil with the film is inserted into a plastic vacuum cassette. The films are exposed by the Dy foil overnight and are developed the next day.

For routine neutron radiography the double coated D4 X-ray film is used, as with this film shorter exposures can be used providing a larger number of neutron radiographs. The single coated SR film is used in special instances, where neutron radiographs of higher quality are required and the longer exposure time is acceptable.

6. EXPOSURE PROCEDURE

The fuel rod under examination is exposed through both neutron ports (4 on Figure 1). The first exposure starts when the top of the rod is positioned approximately in the middle of the right part. Simultaneously with the exposure through the right port an exposure through the left port occurs. Due to the differences in the neutron flux intensities the exposure through the left port is a little shorter than through the right port (25 and 30 min respectively for the D4 film). The rod is moved in stages to cover the entire length.

At the bottom of each neutron port, two cobalt wires are located which serve to provide a positioning index on each film. The developed films are eventually assembled in such a way as to give a single neutron radiograph of the whole rod.

7. ASSESSMENT OF NEUTRON RADIOGRAPHS

The search for defects is concentrated on five areas of the rod: fuel, cladding, plenum, plugs and instrumentation, which may be included in the fuel rod.

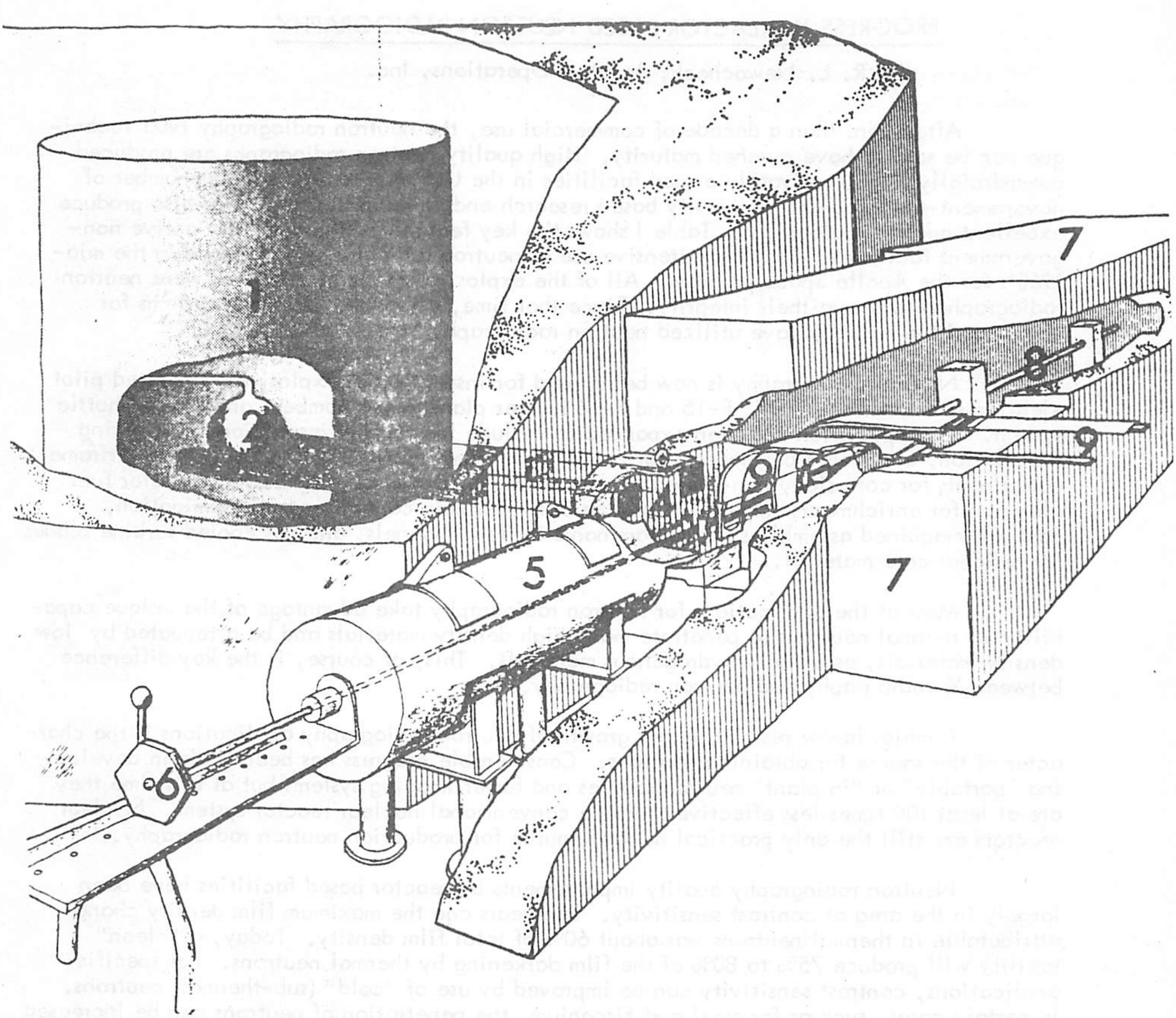
In the fuel, pellets are examined for cracks, chips, dishing and central void. Fuel-to-clad and pellet-to-pellet gap are revealed and assessed. The presence of hydrides in the cladding or plugs can also be revealed.

All irregularities in the plenum (spring, spring sleeve or disc displacement) are well visible or the radiographs.

The fuel column length as well as top of fuel column to plug distance is measured.

An attempt was made to introduce a classification of defects revealed by neutron radiography, in which 20 types of defects in the above mentioned five areas are assessed according to their location and intensity.

Fig. 1. Double beam neutron radiography facility at Risø.



1. Graphite reflector
2. Reactor core
3. Two graphite blocks removed
4. Two neutron beams (10 x 10 cm)
5. Lead container to transport and handling of irradiated fuel rods
6. Rod to positioning of fuel rod during radiography
7. Concrete blocks for radiation shielding
8. Tube supporting the fuel rod
9. Mechanism for introduction of imaging foils behind fuel rod to be radiographed.

PROGRESS IN REACTOR BASED NEUTRON RADIOGRAPHY

R. L. Newacheck, Aerotest Operations, Inc.

After more than a decade of commercial use, the neutron radiography NDT technique can be said to have reached maturity. High quality neutron radiographs are produced commercially by four privately owned facilities in the U.S.A. A much larger number of government-operated and University based research and development facilities also produce excellent quality radiographs. Table I shows the key features of the currently active non-government facilities. The first extensive use of neutron radiography was begun in the mid-1960's for the Apollo Space program. All of the explosively operated devices were neutron radiographed to assure their integrity. Since that time, all man-rated space systems for NASA and the military have utilized neutron radiography extensively.

Neutron radiography is now being used for inspection of explosively operated pilot ejection systems in the F-14, F-15 and F-16 fighter planes, B-1 bomber, and Space Shuttle system. It's application has been expanded to include the routine inspection of "O" ring installation, electronic components for potting integrity, epoxy bonding, aluminum airframe components for corrosion, non-fueled reactor elements for poison distribution, reactor fuel elements for enrichment, impurities, and defects, ceramic capacitors for delamination, cast and machined assemblies for contaminants in flow channels, and gas cooled turbine blades for residual core material.

Most of the applications for neutron radiography take advantage of the unique capability of thermal neutrons to penetrate many high density materials and be attenuated by low density materials, especially hydrogenous materials. This, of course, is the key difference between X-radiography and neutron radiography.

A major factor restricting the growth of neutron radiography applications is the character of the source for obtaining neutrons. Considerable progress has been made in developing "portable" or "in plant" neutron sources and faster imaging systems but at this time they are at least 100 times less effective than the conventional nuclear reactor system. Nuclear reactors are still the only practical neutron source for production neutron radiography.

Neutron radiography quality improvements by reactor based facilities have been largely in the area of contrast sensitivity. Ten years ago the maximum film density change attributable to thermal neutrons was about 60% of total film density. Today, a "clean" facility will produce 75% to 80% of the film darkening by thermal neutrons. For specific applications, contrast sensitivity can be improved by use of "cold" (sub-thermal) neutrons. In certain cases, such as for steel and zirconium, the penetration of neutrons can be increased by more than 10 fold by using cold neutrons rather than thermal. On the other hand, other materials such as boron and hydrogen have much higher attenuation coefficients for cold neutrons.

A beam purity indicator (BPI) and a set of sensitivity indicators have been adopted by the ASTM as a standard method for determining image quality. The BPI provides information about the contrast capability of the facility including separate indications for beam gamma and scattered neutrons. The sensitivity indicators provide information concerning the ability to see various sizes and types of defects in different thicknesses of a plastic step wedge. The ASTM approved indicators are fully discussed in "Standard Method for Determining Image Quality in Thermal Neutron Radiographic Testing", ASTM E 545-75.

Presently, there is a serious effort to develop a technique for indicating the inherent sharpness capability of a neutron facility (L/D ratio). The preferred techniques use a standard comparison set of images to which a facility can relate its image of the standardized object. This technique provides a visual acceptance criteria which is more meaningful than the previously used L/D ratio.

TABLE I

Neutron Radiography Facility Comparison

Commercial Production Facilities	Reactor Power KW (th)	Flux @ Film Plane n/cm^2-Sec (Std L/D)	Range L/D available	Film Size available (inches)	Horizontal or Vertical Beam	Source to Film distance "L" inches
Aerotest Operations, Inc. San Ramon, Ca.	250	1 x 10^7	63-500	14 x 17 17 x 17	V	250
Atomics International Canoga Park, Ca.	3	Not disclosed	(1) 64 (2) 80	14 x 17	(1) V (2) H	(1) 128 (2) 160
General Electric Co. Pleasanton, Ca.	100	(1) 2 x 10^6 (2) 3 x 10^6	(1) 70-300 (2) 150-300	14 x 17 17 x 17	(1) H (2) H	(1) 100-275 (2) 300
Cryogenic Technology, Inc. (Using General Atomic Co. Reactor) San Diego, Ca.	(1) 1500 (2) 250	(1) Not disclosed "Cold" Neutron facility (2) 2 x 10^6	(1) Not disclosed (2) 50 or more	(1) 14 x 17 (2) 14 x 17	(1) V (2) V	(1) 260 (2) 216
Active University Facilities						
University of Missouri Columbia, Missouri	10,000	1 x 10^7	45-400	14 x 17	H	112-240
Oregon State University Corvallis, Ore.	1000	4 x 10^7	100-600	10 x 10	H	93
North Carolina State Univ. Raleigh, N. C. (Planned initial operation late 1977)	1000	Not available	120	10 x 10	H	136

NOTES: (1), (2), refer to multiple facilities . Government facilities and nuclear fuel inspection facilities not included. An excellent review of facilities in the United Kingdom and France are included in the "Neutron Radiography Newsletter" No. 14 available from the ASNT, 3200 Riverside Drive, Columbus, Ohio 43221.

Progress In NR For The Nuclear Industry

J.P. Barton

Oregon State University
Corvallis, Oregon 97331

Many nations have constructed their own NR facilities for nuclear fuel evaluation. Examples of some of the larger of these facilities are listed in Table 1. A point to notice here is that the power (usually related to neutron intensity) available at many of these facilities is two orders of magnitude greater than that available at the centers performing highly successful general industrial neutron radiography. For certain specialized applications, such as those involving use of selected energies of neutrons, the higher fluxes will be useful.

In many countries the diversity of application justifies more than one facility. For example, over forty such installations have been commissioned on existing reactors in the five countries Britain, France, Germany, Japan and the USA.

This year two new reactors are being installed specifically for neutron radiography of nuclear fuel. One, at the Hanford Engineering and Development Laboratory, is designed initially for examination of large quantities of unirradiated nuclear fuel.(1) It entered service in April, 1977. The other, at Argonne-West, is designed primarily for examination of highly radioactive fuel in the hot cell complex. It is in an advanced stage of construction.(2)

Whereas the majority of general industrial NR is performed for quality control on manufactured products the majority of NR in the nuclear industry is concerned with design and development programs. One consequence is that unusual applications frequently arise calling for highly specialized techniques. Another consequence is that much of the work is proprietary in nature, and is not reported.

Neutron radiography for nuclear applications, unlike general application work, places considerable reliance on use of gamma insensitive imaging techniques such as dysprosium foil activation transfer, or track etch imaging using boron and lithium converters. Indeed the track etch imaging has been specifically developed for the purpose of radiographing large quantities of light water reactor fuel.(3)

Another technique unique to the nuclear industry is the use of underwater exposure facilities. Seven underwater systems have been constructed in France alone, and this approach is used at the high intensity facility at Oak Ridge National Laboratory in the USA.

The ability to distinguish between isotopes of the same element is of prime importance in some nuclear applications. This, and the need to penetrate considerable thicknesses of comparatively dense material, leads to increasing emphasis on resonance energy neutron techniques as an alternative to thermal neutron techniques. For example the subtraction of two neutron radiographs taken with different resonance filters in the beam can reveal the location of isotopes with certain high resonance cross sections in the object.(4)

Thermal neutron radiography can be used to reveal uranium 233 in a single thorium pin, or plutonium 239 in a single pin consisting mainly of natural UO_2. However, to penetrate objects of higher enrichment or greater thickness, resonance energy neutrons are preferable. (5-6)

Other sophisticated techniques can be useful including use of cold neutrons and microdensitometer film analysis for applications such as precision measurement of fuel swelling following burn up(7), or detection of minute quantities of hydrogen in zirconium(8-9).

Applications in the nuclear industry have not been limited to fuel inspection. Neutron radiography was, for example, the only NDT technique that could sufficiently detect faults in brazed joints between fine wall tubes and heavy flanges in an important reactor pressure circuit(10).

References

1) C.N. Jackson, Jr. et al. "Neutron Radiography of Fuel Pins" ASTM Special Publication 586. Ed. H. Berger, Editor January, 1976.

2) W.J. Richards and W.E. Stephens, "Design of HFEF/N Neutron Radiography Facility". To be submitted to American Nuclear Society Winter meeting, 1977.

3) G. Farny, "Neutron Radiography of Irradiated Fuel Elements Using Cellulose Nitrate Film" Brit. Nuc. Energy Soc. Conf. M.R. Hawksworth, Editor, 1975.

4) H. Reijonen and P. Jauho, "On the Determination of Pu^{239} and Pu^{240} from Reactor Fuel by Neutron Radiography with Filtered Beams". Technical Research Center of Finland, Electrical and Nuclear Technology Publication 4. Helsinki, 1973.

5) A.R. Spowart, "The Advantages of Epicadmium Neutron Beams in Neutron Radiography". Nondestructive Testing, February, 1968.

6) J.P. Barton, "Neutron Radiography for Nuclear Fuel Assemblies". 8th World Conf. on NDT, France, 1976.

7) J.C. Domanus, "Accuracy of Dimensional Measurements from Neutron Radiographs of Nuclear Fuel Pins". 8th World Conf. on NDT, France, 1976.

8) A.M. Ross, "Detecting Cladding Leaks in Irradiated Fuel Elements by Neutron Radiography". ASTM Special Technical Publication 586. H. Berger, Editor, January, 1976.

9) S.J. Crutzen et al., "Use of Neutron Radiography for Quantitative Measurements of Sorbed Hydrogen in Getters and Quality Control of Nuclear Pins". International Seminar on Nuclear Fuel Quality Assurance. OSLD, May, 1976. IAEA St 1/PuB) 435.

10) T.J.M. Robertson, "The Development, Operation, and Present Position of Neutron Radiography in the UKAEA". Euratom Report 1DWG 74/P 3.1. May, 1974.

TABLE 1

Examples of NR Facilities Installed for Fuel Examination

Country	Center	Reactor	Power
France	Saclay	Osiris	70 MW
Belgium	Mol	BR 2	70 MW
W. Germany	Karlsruhe	FR 2	50 MW
Sweden	Aktiebolaget	R 2	50 MW
Holland	Petten	HFR	45 MW
Canada	Chalk River	NRX	30 MW
U.K.	Harwell	DIDO	22 MW
Japan	Tokai-Mura	JRR	2 MW
USA	Oak Ridge	ORR	5 MW
	HEDL	NRR	250 KW
	GE Vallecitos	NTR	100 KW
	ANL-W.	TREAT	80 KW

SEVEN-DIMENSIONAL RADIOGRAPHY

A. DeVolpi
Argonne National Laboratory
Argonne, Illinois 60439

Traditional application of nuclear radiation to re-create graphic images of optically opaque bodies has centered around planar reconstruction of material-density variations. There now exist well-established extensions of these techniques to a third space dimension, and there have been some applications using time-resolved images. This paper will discuss further dimensional attributes of penetrating nuclear radiation.

At TREAT nuclear test reactor in Idaho, the hodoscope system [1.2] has been operating with an ability to collect data in five simultaneous dimensions -- two dimensional space, continuous time resolution, and the ability to distinguish between two types of materials. Plans are being made for extension to seven simultaneous dimensions -- adding the third spatial component and the capability to differentiate a third material.

The TREAT reactor causes fissions in a sample of test fuel at the center of the reactor. The hodoscope, which consists of a collimator with over 300 channels, monitors radiation emitted from the test sample through a slot within the reactor. The hodoscope system seeks to observe the spatial redisposition of the constituents of the test -- uranium or plutonium fuel, steel cladding, and sodium coolant -- during such a test, whose duration typically ranges from 300 msec to 30 sec.

The result of this instrumentation is a series of time-resolved "radiographs" of the dimensional and density characteristic of each of the major reactor constituents. Time resolution can be less than a millisecond, and deadtime is less than 10%.

Penetrating fast neutrons and gamma rays are utilized to obtain the necessary results. Although spacial resolution is sacrificed during transient tests, the hodoscope can be operated prior to or after a transient in a higher resolution mode. In this respect, the hodoscope is being developed for use in tomographic applications with penetrating radiation from a stable source.

[1] A. DeVolpi, et al., "Fast Neutron Hodoscope at TREAT: Development and Operation," Nucl. Techn., 27, 449 (Nov. 1975).

[2] A. DeVolpi, et al., "Fast Neutron Hodoscope at TREAT: Data Processing, Analysis, and Results," Nucl. Techn., 30, 398 (Sept. 1976).

EXACT DIMENSIONAL MEASUREMENTS IN NEUTRON RADIOGRAPHY

A.A. Harms
McMaster University
Hamilton, Ontario, Canada L8S 4M1

One of the more significant and interesting recent applications of neutron radiography is the determination of dimenional variations in radioactive nuclear fuels. In these applications, the principle objective is to locate the edge of the radiographed object on the basis of a spatially varying optical density on the film.

Several researchers have recently addressed themselves to this radiographic measurement problem and have employed some empirically developed criteria for this purpose. Aside from the agreement on the importance of this problem and the realization that many factors have a bearing on it, no widely accepted methodology which consistently yields accurate dimensional measurements has emerged.

We investigate here this dimenionality problem on the basis of some fundamental considerations. As one approach, we incorporate both the neutron conversion process in the converter and the characteristic curve of the film into one graphical algorithm. Figure 1 provides a schematic representation of the correlation between the converter response and the film response for the case of an ideal knife-edge object. As is evident, variations in either of these curves - which depend upon the radiographic system used - will lead to relatively different optical density ratios D_o/D_{Max} associated with the position of the edge of the object.

The case of radiographing a nuclear fuel pin is more complex because of geometric and burnup effects. We have mathematically analyzed each of these contributions and illustrate a typical result in Figure 2. The important optical density variation caused by burnup is dramatically apparent.

In general, we have found that unless the detailed neutron imaging and fuel characteristics are included significant errors in dimensional measurements of nuclear fuel pins are highly likely.

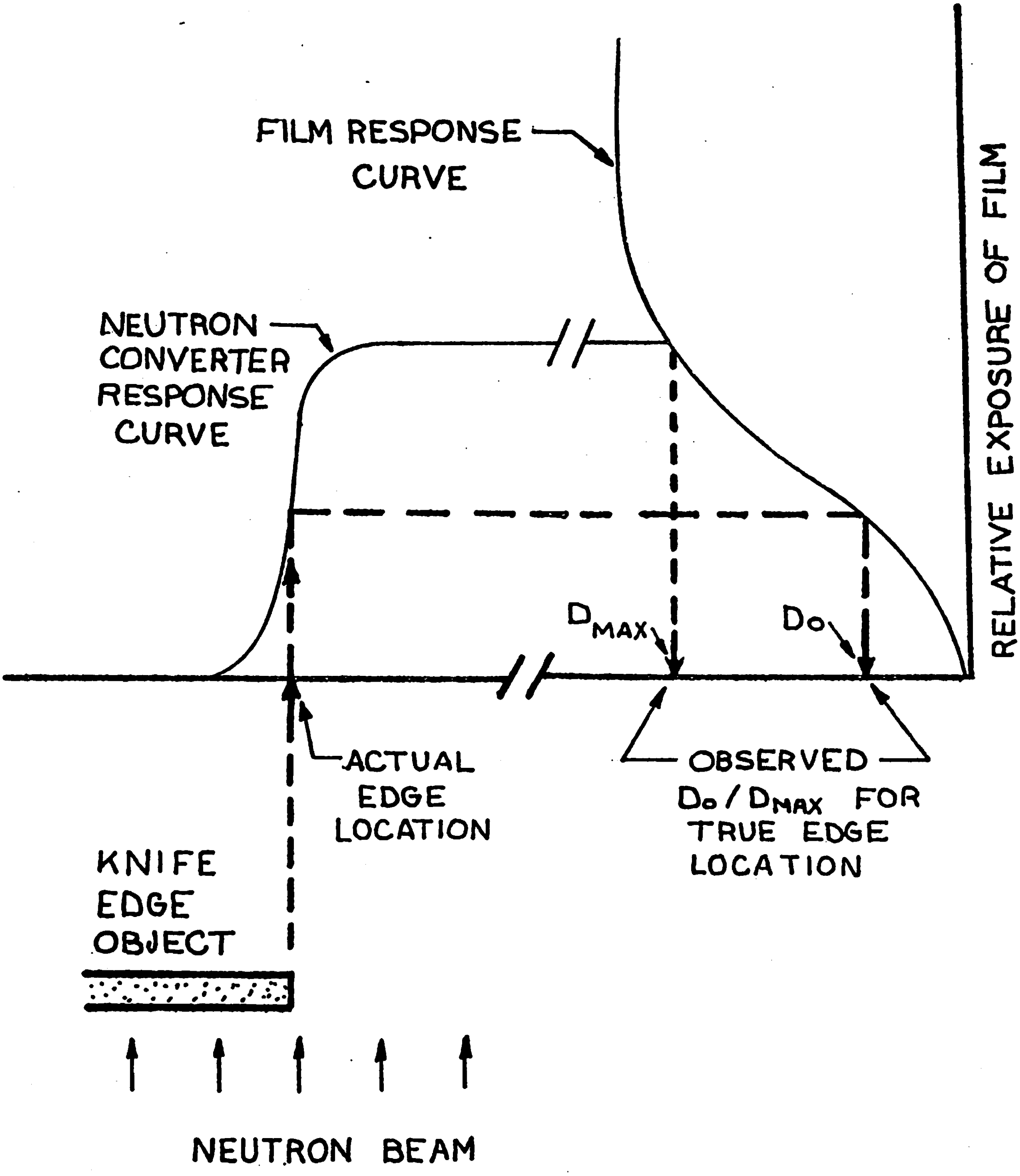


Fig. 1: Illustration showing the role of the neutron converter response curve and the film response curve in the determination of D_o/D_{Max} for the correct location of the object's edge.

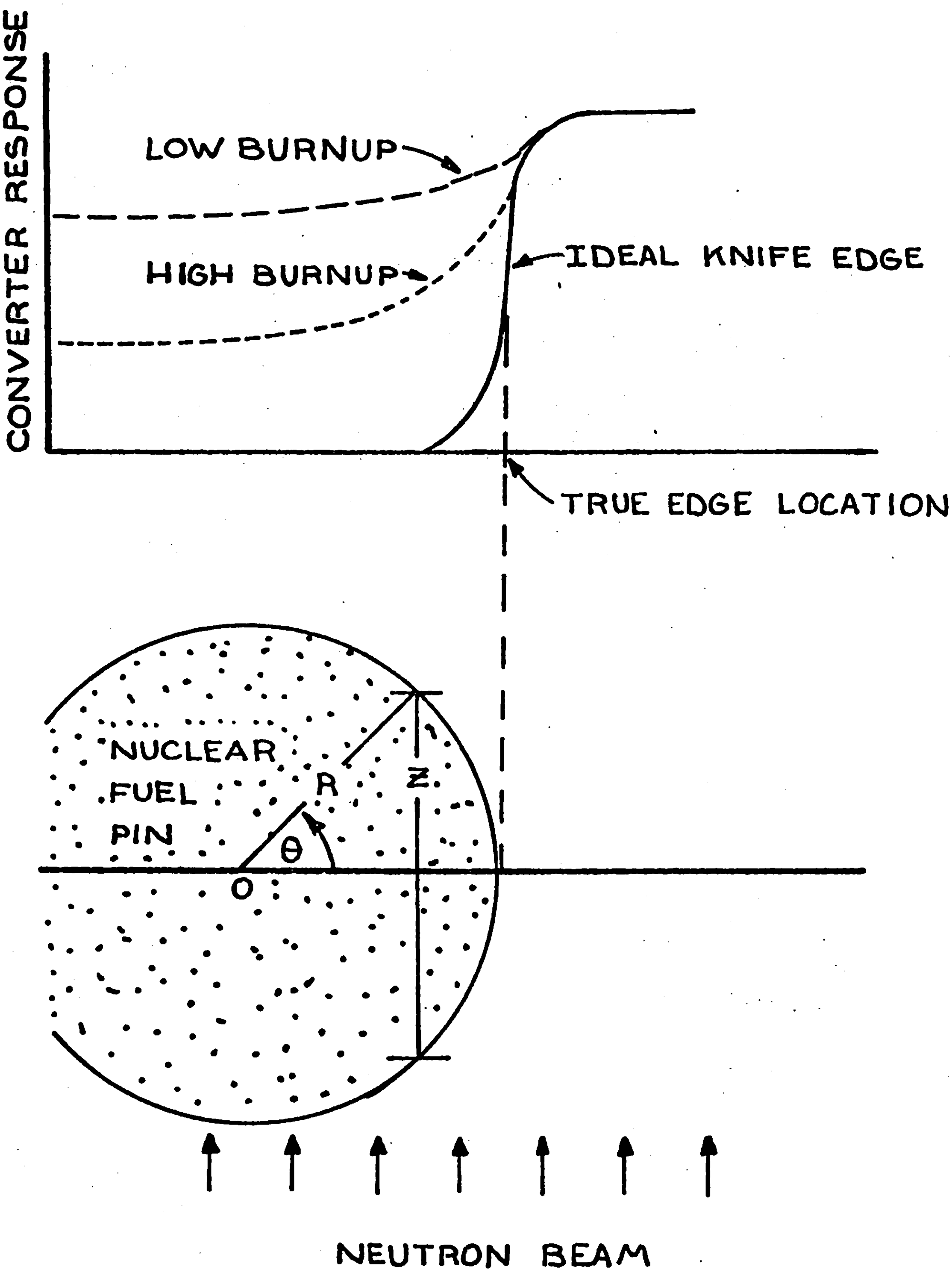


Fig. 2: Schematic depiction of the neutron converter response as a function of low and high burnup. The x-axis of the converter response has been expanded to illustrate effect.

COLOR IMAGE PROCESSING TECHNIQUES FOR NEUTRON RADIOGRAPHS

V. Panhuise, S.R. Bull and J. Seydel
University of Missouri

A method to convert a black and white radiographic image to a color image has been developed. This project is one step in the development of a portable neutron radiography system coupled to a video monitor with computer-controlled automatic inspection capability. The human eye is considered by many to be more sensitive to color differences than gray shades. Therefore, 64 color shades were used to encode the gray shades during the processing of the radiographic images. For the development effort in progress, a reactor-based neutron radiography facility is employed. The facility is located at the University of Missouri research reactor. The flux at the object can be varied from approximately 6×10^4 to $1.6 \times 10^8 n/cm^2$-sec, and the gamma dose rate varies approximately 1.12 to 3.0 mR/sec. Radiographs are taken at this facility and then processed at the Advanced Automation Computer Laboratory, University of Missouri-Columbia.

A radiograph is scanned with an image dissector camera using standard 35 mm lenses. The radiograph is scanned and the density is digitized in a 240 x 256 array. The camera may be focused on select portions of the radiograph, so magnification can be used in this step.

Software programming is used to generate the color image which is displayed on a RAMTEK color display. The program allows the selection of 1 to 64 colors which were chosen from 4096 colors generated by the computer system. After choosing the 64 colors they were ordered according to the color spectrum for easy gray shade identification. The scanner can read 256 gray shade levels with zero corresponding to the brightest shade and 255 in the darkest. The program allows the selection of gray shade levels but the number of gray shades must always exceed the number of colors chosen. The program then associates each gray shade with a color, such that a calibration between color number and gray shade level can be obtained. This calibration is of obvious importance in the portable system where no intermediate step is taken to produce a radiograph.

Preliminary results of this programming technique show that the same information is available through the use of color processing. Figures 1 and 2 are some examples of the process. Figure 1a is a radiograph of a compact tension specimen under no applied load. Figure 1b is a color reproduction of this radiograph using 64 colors representing 256 gray shades. Symmetric variations of colors evident about the center of the specimen result from the use of a circular aperture at the radiography facility. Figure 2a is a radiograph of the system image quality indicator (SYQI) and Figure 2b is the corresponding color reproduction. It can be seen that all holes are visible and the resolution is maintained even though edge sharpness is diminished. The color image processing technique is useful because of immediate recognition of color variations whereas by comparison variations in gray shades are not always readily apparent.

Presently, research is being continued with image filtering techniques. The filtering process is being developed with the goal of decreasing the noise levels associated with the aperture size and any other background noise. Edge enhancement techniques may also complement the color image processing technique.

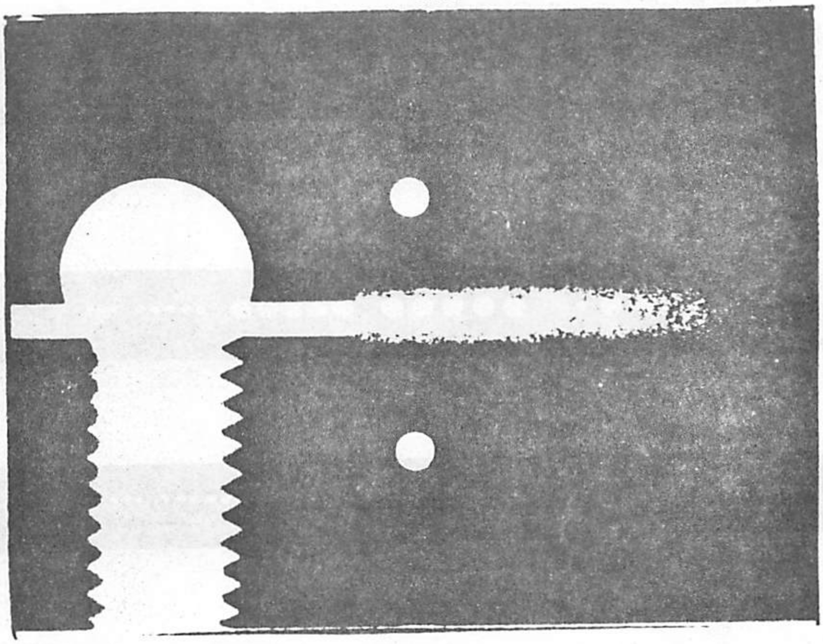


FIGURE 1a

Neutron Radiograph of Compact Tension Specimen

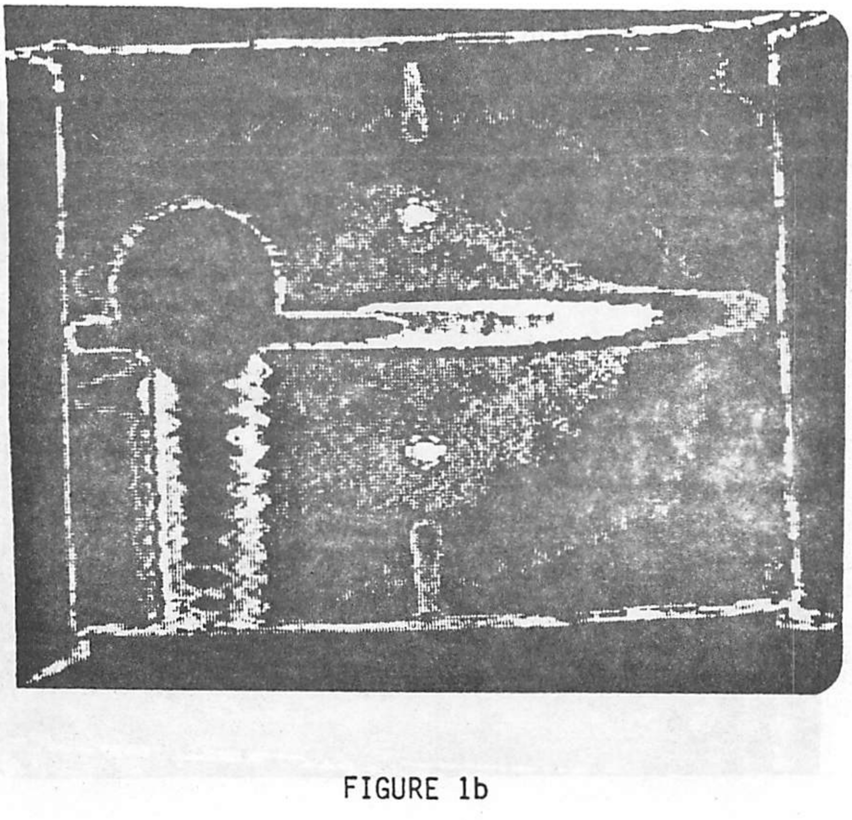


FIGURE 1b

Color Reproduction of Figure 1a
Colors - 64
Gray Shades - 256

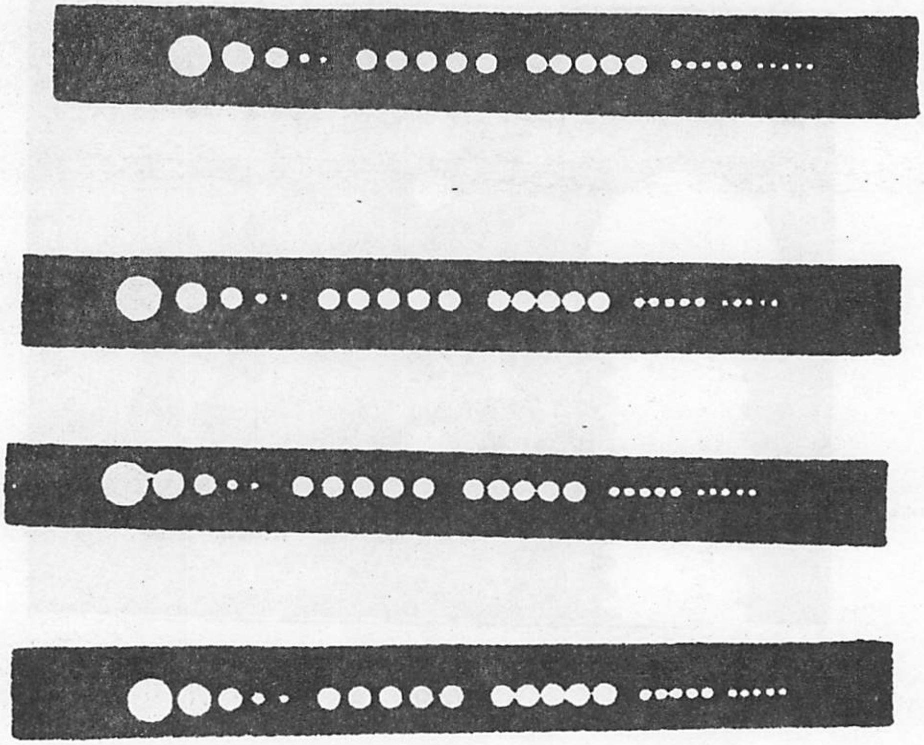


FIGURE 2a

Neutron Radiograph of SYQI

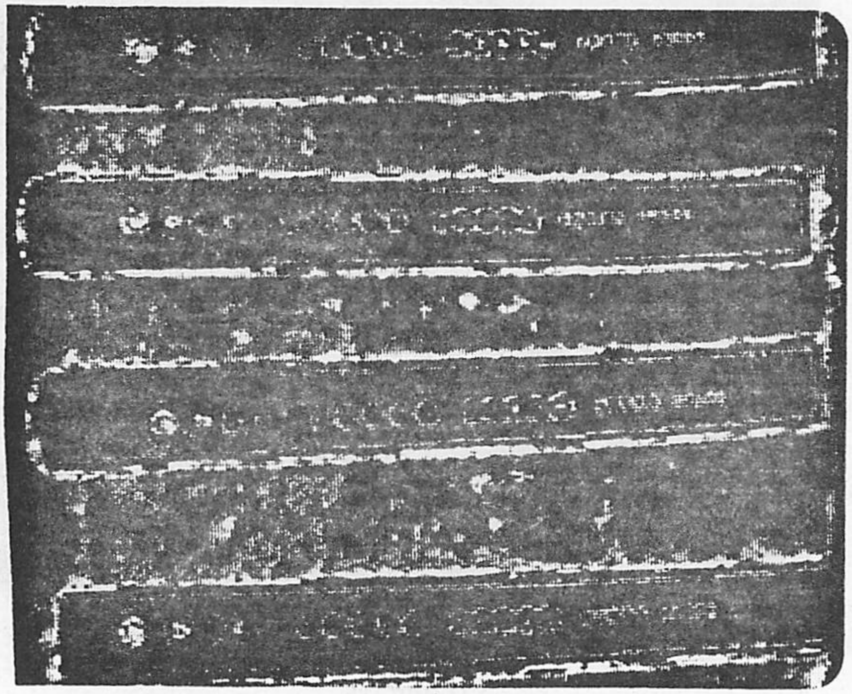


FIGURE 2b

Color Reproduction of Figure 2a
Colors - 32
Gray Shades - 95

XERORADIOGRAPHY WITH NEUTRONS

W. L. Parker*
Institute for Materials Research
National Bureau of Standards
Washington, DC 20234

Xeroradiography has become increasingly important in diagnostic radiology over the last several years. One of the reasons for this is the "edge effect," an enhancement of small differences in object density which results in improved contrast and increased accuracy in interpretation of the radiograph. This research was undertaken to see if the technique could be applied to neutron radiography to produce the same enhancement of the image.

In the xeroradiographic process the image is formed electrostatically on a layer of selenium (Se) 0.012 mm thick deposited on an aluminum (Al) backing plate. Before exposure, charge (+) is sprayed uniformly on the Se to produce a potential difference across the Se of from 1000 to 1500 volts. The potential difference is reproducible and can be varied. When exposed to ionizing radiation, the Se becomes conducting, the charge leaks off to the grounded backing plate in an amount proportional to the exposure provided that saturation does not occur, and the resulting pattern of surface charge distribution is the "image." It is developed by spraying on a cloud of charged fine powder, blue in color, which adheres to the Se in some places but not in others. The resulting image can be either a positive or a negative, depending on the potentials applied to electrodes in the developing chamber. The image is then transferred to a specially coated paper to which it is thermally bonded to form the final radiograph. The edge effect results from distortion of the electric field lines at a discontinuity in the surface charge density with a resulting apparent greater difference in density on the radiograph.

To avoid absorption and scattering of the neutrons by the plastic wall of the cassette a window was cut in one wall and the plastic replaced by a 0.63 mm Al sheet. The first successful radiographs were made by putting a converter screen inside the cassette. It was a 0.012 mm gadolinium (Gd) film vapor-deposited on a 3.13 mm Al plate. It was used as a back screen, i.e. the neutron beam passed through the Al window, the Al plate, and then the Se before striking the Gd, which was separated from the Se by approximately 0.6 mm. Compared to AA film, the required exposure for an optimum radiograph was roughly double, but the resolution was considerably poorer. Much better radiographs were obtained using a gadolinium oxysulfide screen mounted on a cardboard backing and also about 0.6 mm from the Se. Optimum exposure was comparable to that for AA film--about 10^8 neutrons/cm^2--and resolution was in the positive mode comparable to AA and definitely superior to that for faster emulsions. Resolution in the negative mode is quite inferior, and the edge effect is greatly reduced. The latter effect is also observed in xeroradiography with x-rays.

Preliminary applications of the technique have been most encouraging, giving particularly good results with samples of aluminum corrosion and ancient Chinese art objects. In addition to the high caliber of the radiographs, other advantages are the absence of the dark room and the capability of having a finished radiograph some two minutes after completing the exposure.

We have also tried screens consisting of gadolinium oxide paint applied to a lucite plate. The quality of the resulting radiographs is comparable to those made using the gadolinium oxysulfide screen. The exposure time is increased by about one-third. We conclude from this that most of the image produced by the gadolinium oxide screen is produced by electrons emitted following neutron capture by the Gd nuclei and not absorbed in the screen and much less by visible light emitted when the electrons are absorbed in the screen.

Perhaps the most interesting result is that moving the screen approximately 1.0 mm further from the Se surface produced almost no degradation in the image. Apparently the electrons, which are emitted isotropically, follow the field lines to the Se. It seems surprising that fields produced by a difference of potential of about 2000 volts have that much effect on electrons whose energy at emission is of the order of 70 Kev. Hopefully, further experimentation will provide an explanation.

We acknowledge with thanks the loan of the equipment to the Reactor Radiation Division by the Xeroradiography Division of the Xerox Corporation. This project was originally conceived at Reed College in connection with research contracts funded by the Dental and Surgical Branches of the U. S. Army Medical R. & D. Command.

---

*Summer Faculty Appointee, National Bureau of Standards.
Permanent Address: Department of Physics, Reed College, Portland, OR

QUANTITATIVE DETERMINATION OF CORROSION IN ALUMINUM STRUCTURES USING NEUTRON RADIOGRAPHY

Joseph John and H. Harper
IRT Corporation, San Diego, California

SUMMARY

A number of programs have been conducted at IRT Corporation to develop and evaluate neutron radiography as a nondestructive inspection technique for the detection and identification of surface and intergranular corrosion in aluminum aircraft structure. In these studies the ability of neutron radiography to detect corrosion has been clearly established. Its ability to image corrosion, whether it is hidden behind thick pieces of metal, or present at the interface of two metallic components, is particularly suited for inspecting aircraft.

A program has been carried out to evaluate the potential of using this technique as a quantitative tool to measure the extent of corrosion so that rework decisions could be made based on these radiographs. Results of this investigation show that an experimental relationship can be formulated which quantitatively determines the corrosion depth from film densities with a precision of 2-3%. These results have been verified with controlled samples as well as actual aircraft components.

This basic procedure has been extended to many random samples of aircraft skin and substructure containing surface and subsurface corrosion. These samples are made of different alloys of aluminum, and have been exposed to a variety of environmental conditions during service. In these cases, the quantitative measurements were made with a precision of ±10%.

These measurements indicate that the extent of corrosion can be determined with a precision of ±10% without any detailed knowledge of aircraft model, type of alloy used, or its prior service and rework history.

PERFORMANCE OF AN INEXPENSIVE COLD NEUTRON RADIOGRAPHY FACILITY

R.H. Bossi and J.P. Barton
Oregon State University
Corvallis, Oregon 97331

Thermal neutrons have a range of energies generally following the Maxwell-Boltzman kinetic energy distribution of the moderator atoms with which they are colliding. The mean thermal neutron energy is about 0.025 eV for moderator at room temperature. Cold neutrons are a portion of the thermal neutron energy distribution at the low energy (long wavelength) end. A common definition is those neutrons below 0.005 eV, since this is the cut off of an efficient filter material (beryllium). At room temperature about 5% of the Maxwell-Boltzman distribution lies below 0.005 eV. The proportion can be increased by cooling the moderator.

There are many neutron radiography applications for which use of cold neutrons, or at least a soft energy spectrum of neutrons, may be advantageous. Some materials, such as hydrogen, are more opaque and therefore more visible when using cold neutrons, while other materials, such as crystalline metals, are more transparent.(1-4) One example where neutron spectrum control is useful is in examination of nuclear fuel pins. To penetrate the fuel a relatively hard energy spectrum is required: to obtain a precision measurement of the fuel pellet diameter inside the can a relatively soft energy spectrum is required. For Fast Flux Test Facility fuel the attenuation across the pellet diameter can be increased from a factor of 12 to a factor of 300 by changing from thermal to cold neutrons.

Neutron radiography facilities that provide for control of spectrum from say thermal to cold or partially subthermal neutron energies have not yet been widely adopted. This paper describes such a facility recently installed at the Oregon State University TRIGA reactor. The main message is that conversion from hard spectrum to soft spectrum can be provided very inexpensively, and that significantly extended usefulness of neutron radiography can result.

Although some cold neutron beam facilities have a cryogenically cooled moderator volume at the source end of the beam, it is argued that this expensive item is not essential for neutron radiographic purposes. The conversion of the beam from a full Maxwellian spectrum to a subthermal beam is primarily dependent on good filter design. A cryogenically cooled source only serves to increase the available cold neutron intensity, usually by a factor of less than 10. Thus, it may be better to extract a beam from a high flux region and work with filter only, rather than use a comparatively low flux region in which can be placed a refrigerated source.

A good filter design would consist of polycrystalline beryllium (20 cm to 30 cm thick), cooled by liquid nitrogen to about 100°K (cooling reduces the beryllium attenuation coefficient for .005 eV neutrons from 0.06 cm^{-1} to 0.006 cm^{-1}). This need not be expensive.

An even simpler and cheaper filter has been used in the present OSU facility. It consists of a cylinder of beryllium 20 cm in diameter and 10 cm thick which is available commercially at about $2,500. For this thickness of beryllium at room temperature, the attenuation of thermal neutrons is about 5×10^3, and the attenuation of .005 eV neutrons is less than a factor of 2. Cooling by liquid nitrogen is therefore unnecessary.

The filter is movable into or out of the beam line (roller shutter #3 in Figure 1) so that the system may be alternated between one with very hard energy spectrum (cadmium ratio for indium = 2) to one with very soft spectrum (The ASTM BIPI gauge shows zero visibility of the holes filtered by 1 mm of boron nitride). Since the beam is designed for radioactive fuel applications, little gamma filtering has been included and only dysprosium transfer or track etch imaging are used. A typical exposure time for dysprosium transfer to Kodak AA film is 30 minutes. This corresponds to a cold beam intensity of about 2×10^5n/cm-sec, which can be compared with the intensity of 1×10^6n/cm^2-sec quoted for the 5 MW HERALD reactor cold beam. (3) For both facilities the collimator ratio is about 100:1. The inexpensive system therefore provides a filtered beam only a factor of five less intense than that at HERALD (which uses a cryogenically cooled moderator volume and a liquid nitrogen cooled 30 cm long beryllium filter). The filtered beam on the OSU TRIGA is, of course, only partially filtered but this degree of inexpensive spectrum control could be important in a variety of applications. (Figure 2)

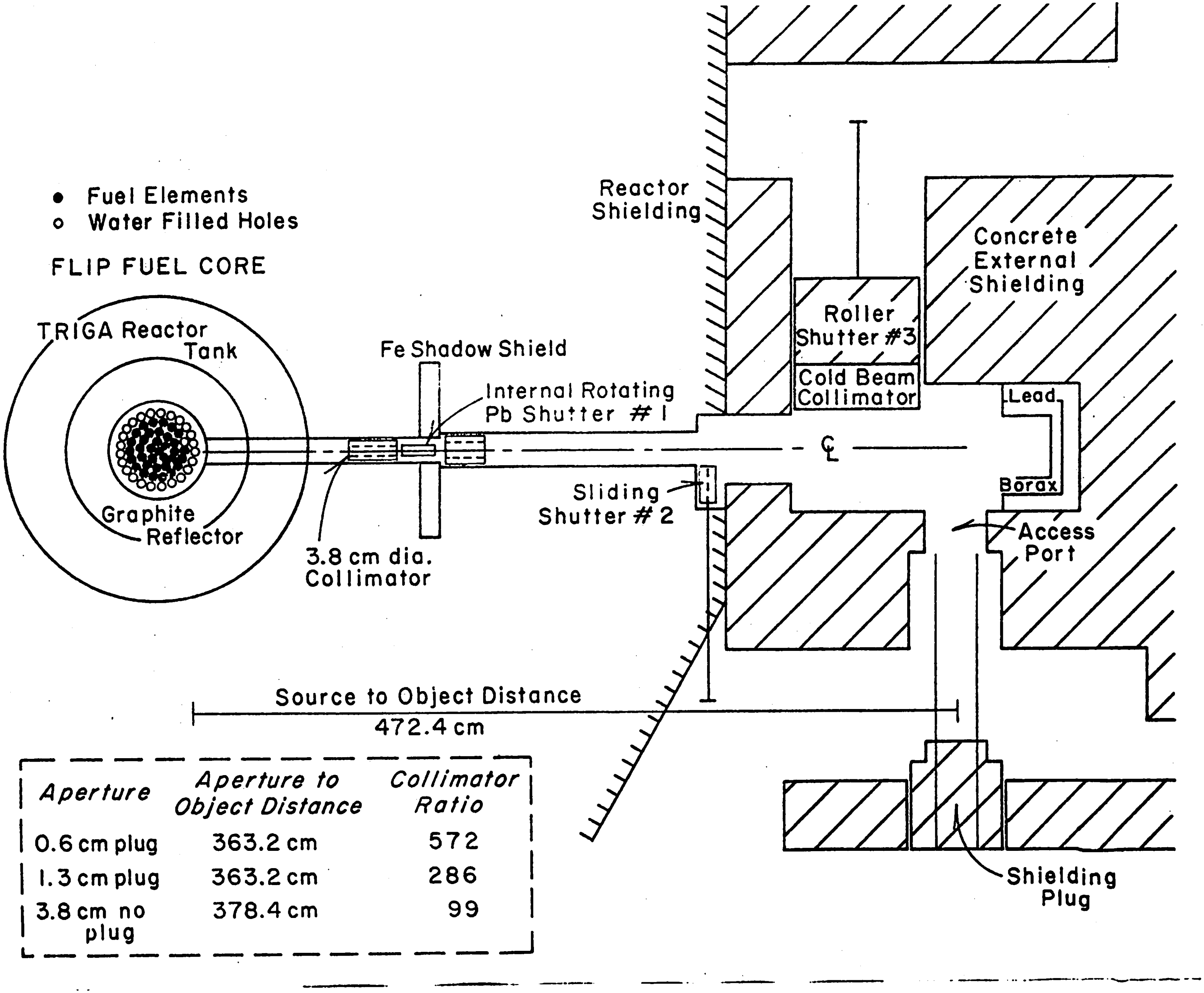
References

1. J.P. Barton, "Radiographic Examination Through Steel Using Cold Neutrons." British Journal of Applied Physics, 16 (1965).

2. J.P. Perves, "Underwater Neutron Radiography - First Results with Cold Neutron Radiography," 6th International Conf., NDT, Germany, 1970.

3. M.T. Hawksworth, J. Walker, "Cold Neutron Beams for Radiography Through Steel," British Nuclear Energy Society Conf. Radiography with Neutrons, 1975.

4. J.C. Bates, S. Roy, "Neutron Radiography with Very Cold Neutrons," Nuclear Instruments and Methods, 120 (1974).

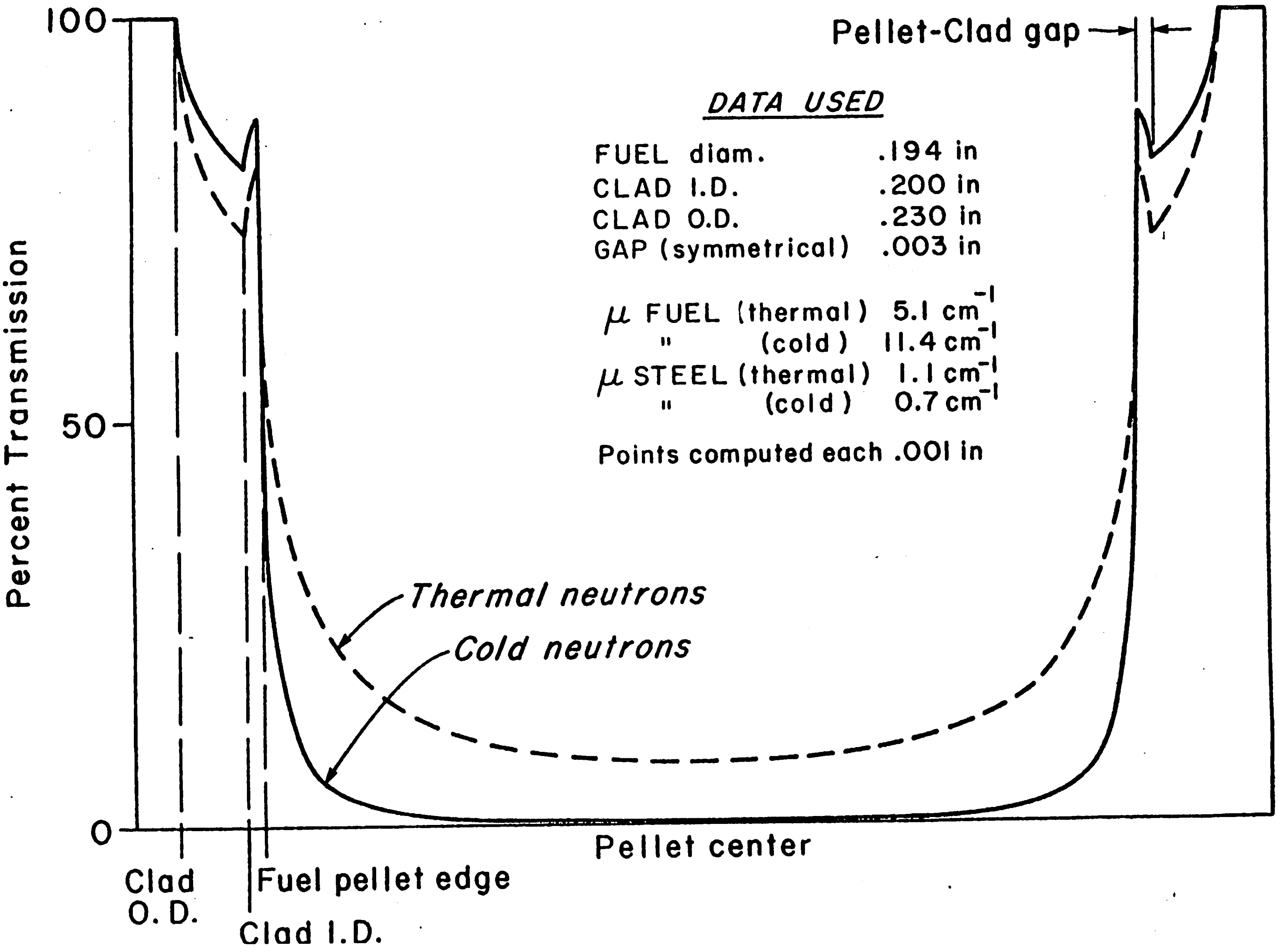


Aperture	Aperture to Object Distance	Collimator Ratio
0.6 cm plug	363.2 cm	572
1.3 cm plug	363.2 cm	286
3.8 cm no plug	378.4 cm	99

Figure 1 Plan showing radial neutron radiography facility.

Figure 2

THEORETICAL NEUTRON TRANSMISSION ACROSS FUEL PIN FOR THERMAL AND COLD NEUTRONS (FFTF FUEL WITH PELLET-CLAD GAP)



SUBTHERMAL NEUTRON RADIOGRAPHY AND CALIFORNIUM-252

J.J. Antal and A.A. Warnas
Army Materials and Mechanics Research Center
Watertown, MA 02172

Crystalline materials may be either very opaque or very transparent to very low energy (subthermal) neutrons in accordance with their crystal structure and the precise neutron energy. This phenomenon can be exploited in the radiography of materials and for the purpose of selecting subthermal neutrons from sources.

Subthermal neutrons can be obtained from nuclear reactor sources by filtering a thermal neutron beam with a polycrystalline beryllium filter. Diffraction scattering in beryllium removes all neutrons of energies greater than 0.005 eV, but only about 1/3% of the original intensity remains. Fortunately an enhancement of the number of subthermal neutrons in a beam can be produced by reducing the temperature of the moderator material from which the neutrons issue. This has been accomplished successfully in a number of reactors with rather complex low temperature facilities.

The large amount of heat induced by radiation into reactor facilities requires that only a small amount of moderator be cooled and that the facility be located away from the highest radiation fluxes. This results in a poor efficiency for the production of subthermal neutrons. This efficiency for any neutron source might be expressed in terms of the fission neutron activity needed to create a flux density of one subthermal neutron per cm^2 in a beam. A rough calculation for an operating reactor source shows this to be approximately 6×10^{11} fission neutrons/subthermal neutron/cm^2. We are interested in knowing what efficiency might be attained with a low temperature facility employing Californium-252 as a source. Californium-252 is a low heat-generating source of high specific neutron activity. These characteristics would seem to allow for a much improved efficiency since the source is small enough that all of the moderator material and the source itself may be cooled completely in a very favorable geometry where the source is totally enclosed by the moderator.

We chose to begin with a 130 mm (5") diameter sphere of paraffin as a moderator with a 2 mg SR-CF-100 Californium-252 source to be positioned at its center. The radial thermal neutron flux profile within the sphere was proved with gold wire dosimetry which showed a strong flux depression caused by the stainless steel source encapsulation and indicated the need for removal of the source eyelet and handling cable. Initially, a 25 mm diameter (1"), 38 mm (1-1/2") deep reentrant hole in the sphere was used as a beam port. Experiments were performed with the sphere cooled by evaporating liquid nitrogen while enclosed in a polyfoam dewar and were successful in producing at -140C a factor of two increase in subthermal neutron flux over that at room temperature.

The beam flux obtained in these experiments was extremely low, 5 n/cm^2/sec, making it apparent that much care would have to be taken to produce a working subthermal source with Californium-252. After improvements were made in the mounting of the sphere and the beam collimation, improving the detection sensitivity by a large factor, measurements could be made to determine the optimum depth of the reentrant beam hole in the sphere. The optimum depth was located as 13 mm beyond the sphere center. The optimum position for the source was found to be critical also. With these improvements in geometry very reproducible data giving the beam intensity as a function of moderator temperature from 20 C to -150 C were obtained. Similar data was obtained for methyl methacrylate and polyethylene by replacing the paraffin plug in the beam hole with those materials.

In these last experiments, a flux of 11 neutrons/cm^2/sec was obtained at -150 C. The source was emitting 3.6x10^9 fission neutrons per second at this time which gives an efficiency for the production of subthermal neutrons of 3.3 x 10^8 fission neutrons/subthermal neutron/cm^2, a value 1800X the calculated reactor efficiency.

With the use of a larger Californium-252 source, better moderator materials than paraffin, less absorbent source encapsulation, and cooling of the beryllium filter, it is estimated that a subthermal neutron flux of 1 x 10^3 may be reached. The additional complexity of a liquid hydrogen moderator may be required to reach the flux levels of thermal neutron radiography.

PERFORMANCE OF A CALIFORNIUM MULTIPLIER (CFX)
FOR NEUTRON RADIOGRAPHY

K. L. Crosbie, J. C. Young, H. Harper and Joseph John
IRT Corporation, San Diego, California

SUMMARY

The simplest neutron radiography system, exploiting the capabilities of ^{252}Cf, consists of a single source within a moderating and shielding medium, usually a tank containing a few hundred gallons of water. In such a device, the thermal neutron flux is peaked at the location of the source with a magnitude of approximately 1 x 10^7 n/cm^2-sec per milligram of ^{252}Cf. When higher flux levels are required, this can be achieved only through the use of more ^{252}Cf with increasing investments in the californium source. For example, to achieve thermal neutron flux levels of 2 x 10^8 n/cm^2-sec in systems with radiography ports, requires 30 mg of ^{252}Cf with an initial cost of over $400,000 for source material and encapsulation and a source replacement cost of more than $100,000 per year.

The Californium Multiplier (CFX) provides an attractive alternative to using such large sources to achieve the desired flux levels. For example, a thermal neutron flux level of 2 x 10^8 n/cm^2-sec has been obtained in CFX radiography systems with only 1 mg of ^{252}Cf. Thus, the CFX has achieved a thermal neutron flux multiplication of 30. The initial cost of the ^{252}Cf is reduced to about $24,000 and the decay of the source represents a cost of only $6,000 per year.

Several CFX systems have been designed, built and tested to date. Neutron radiography systems are available with either horizontal or vertical beam capability. The performance and design characteristics of the system are given in the table.

One important feature of the CFX is its expansion capability. A given CFX system can be easily upgraded to provide higher performance by simply adding more ^{252}Cf. Systems capable of accommodating up to 40 mg of ^{252}Cf have been constructed.

PERFORMANCE AND DESIGN CHARACTERISTICS OF ^{252}CF MULTIPLIER (CFX)

^{252}Cf source	1 mg
^{235}U loading	2000 g
Uranium enrichment	93.4 percent
Fuel form	Clad metal plates
Moderator	Water
Maximum k_{eff}	0.990
Δk_{eff} increase for 20-g ^{235}U sample	0.004
Control poison	Cadmium, Aℓ clad
Thermal flux	2×10^8 n/cm^2-sec
Fast flux	6×10^8 n/cm^2-sec
Thermal flux multiplication	30
Radiography collimator ratio (L/D)	15 or greater
Thermal flux at L = 40 inches	5×10^4 n/cm^2-sec
Film exposure area at L = 40 inches	18 inches x 18 inches
Beam uniformity at L = 40 inches	±5 percent
Neutron/gamma ratio at L = 40 inches	1×10^5 n/cm^2-mR
Cadmium ratio (fission chamber)	15
Dose rate at shield surface	Less than 10 mR/hr
Fission power level	3.8 W

Electronic Imaging Applied to Neutron Radiography

Donald A. Garrett
National Bureau of Standards
Washington, D.C. 20234

Donald A. Bracher
Old Delft Corporation of America
Fairfax, Virginia 20230

Details of an advanced electronics imaging system which has been applied to field neutron radiography are presented in this paper. Heretofore, many applications of neutron radiography have not been utilized due to system mobility and long exposure times. A modified Delcalix image intensifier was used with a Hughes Model 639 Scan Conversion Memory and Neurad-3 Mobile Neutron Radiography system to obtain neutron radiographs on a television monitor in .5 to 10 minutes.

The electronic imaging system consists of a phosphor screen coupled to a light amplifier by a Bouwers' concentric mirror system with an aperature of GRA 1:0.65. The image is transferred from the light amplifier through relay optics to an image isocon television camera. A standard EIA 525 line system is used to interface easily with output devices such as frame integrator, video tape recorder, kinescope, and monitor.

Some application areas of neutron radiographic systems for quality control are discussed, i.e.

1. Aircraft maintenance for detecting corrosion.

2. Ammunition inspection: Charging gradients

3. Biomedical for pathological investigation of bone tumors.

Real time imaging is tied to reactors, accelerators, and large Californium-252 sources.

Field applications dictate small Californium-252 sources for portability. When small sources are used, a frame integrator is added to the system which enables exposures to be made from seconds to ten minutes.

RESONANCE ENERGY NEUTRON RADIOGRAPHY FOR COMPUTERIZED AXIAL TOMOGRAPHY*

C.T. Oien, K. Bailey, C.F. Barton, R. Guenther, J.P. Barton

Oregon State University
Corvallis, Oregon 97331

For neutron radiography of large complex objects there are two potential problems: (1) penetration (can sufficient signal to noise ratio be obtained?) and (2) decoding (can the information be sorted out so that signals from one plane do not hide signals from a plane behind it?). In this study, the large complex object of interest consists of a 217 pin bundle of enriched nuclear fuel arranged in hexagonal arrays. With thermal neutron radiography, transmission can be seen along the clear avenues between fuel pin rows when radiographed in the apex to apex orientation, but thermal neutrons produce no useful penetration of the fuel ($\mu=5.7$ cm^{-1}; attenuation across the 8.4 cm thickness = 10^{21}).

Experiments using material selected to simulate the neutron opacity of real fuel have shown that useful signal to noise ratios can be obtained using filtered beam resonance energy methods (Figure 1). Calculations of the indium resonance reaction rate as a function of neutron energy show that a wide range of neutron energies contribute significantly to the image (Figure 2). These methods have enabled multiple foil packs and alternative materials for resonance detectors to be evaluated. Other calculations have shown that fission neutrons generated in the object by the incident neutron beam will contribute only small noise levels for a wide range of fuel enrichments.

A computer program has been developed which shows at which precise angles the object should orientated relative to the neutron beam, to provide the best signal to noise ratio (Figure 3).

Information decoding is being evaluated using focal plane methods such as multiple film laminography, (1-3) and computerized axial tomography with algebraic reconstruction techniques (4-5), convolution techniques (6), and legendre polynomial techniques (7) (Figure 4).

* Work supported by the U.S. Energy Research and Development Administration through Argonne National Laboratory Contract 31-109-38-3229.

References

1. E.R. Miller, E.M. McCurry, B. Hruska, "An Infinite Number of Laminagneus from a Finite Number of Radiographs," Radiology, 98 (1971).

2. W.L. Parker, H. Berger, N.P. Lapinski, K.J. Reiman, "Three Dimensional Thermal Neutron Radiography," 8th World Conference on NDT, France, 1976.

3. J.P. Barton, "Neutron Radiography for Nuclear Fuel Assemblies," 8th World Converence on NDT, France, 1976.

4. G.T. Herman, A. Lent, S. Rowland, "A Report on the Mathematical Foundations on the Applicability of Real Data of the Algebraic Reconstruction Techniques," J. Theor. Biol., 42 (1973)

5. P. Gilbert, "Iterative Methods for the Three Dimensional Reconstruction of an Object from Projections," J. Theory. Biol., 36 (1972).

6. L.A. Shepp, B.F. Logan, "The Fourier Reconstruction of a Head Section," IEE Transactions in Nuclear Science N-21 (1974).

7. R.B. Guenther, unpublished work, Mathematics Department, Oregon State University.

Figure 1

Penetrating (epithermal) Neutron Radiograph of 91 Pin Bundle of Simulated Fuel Orientated Flat to Flat (0°)

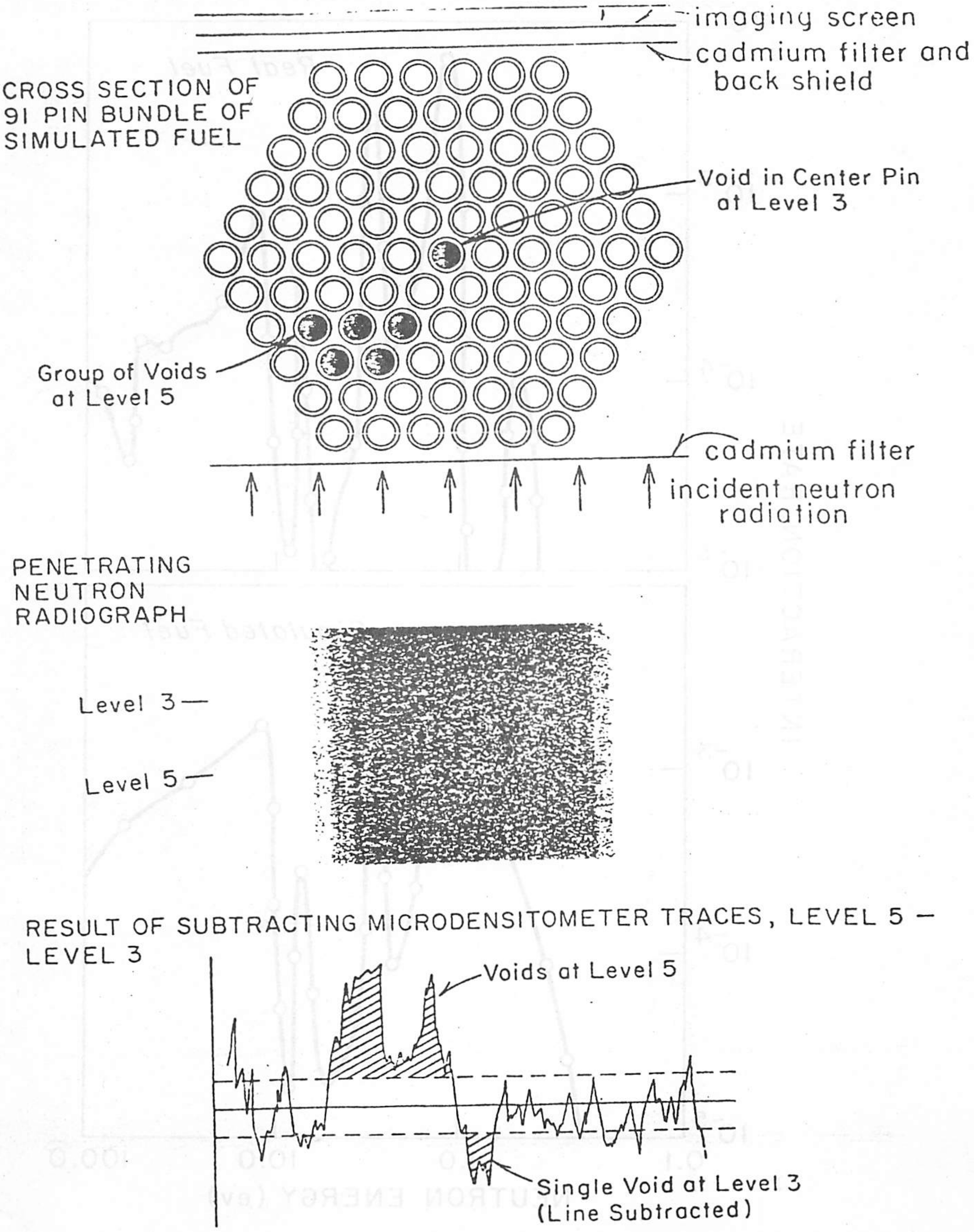


Figure 2. Penetrating (epithermal) neutron radiograph of 91 pin bundle.

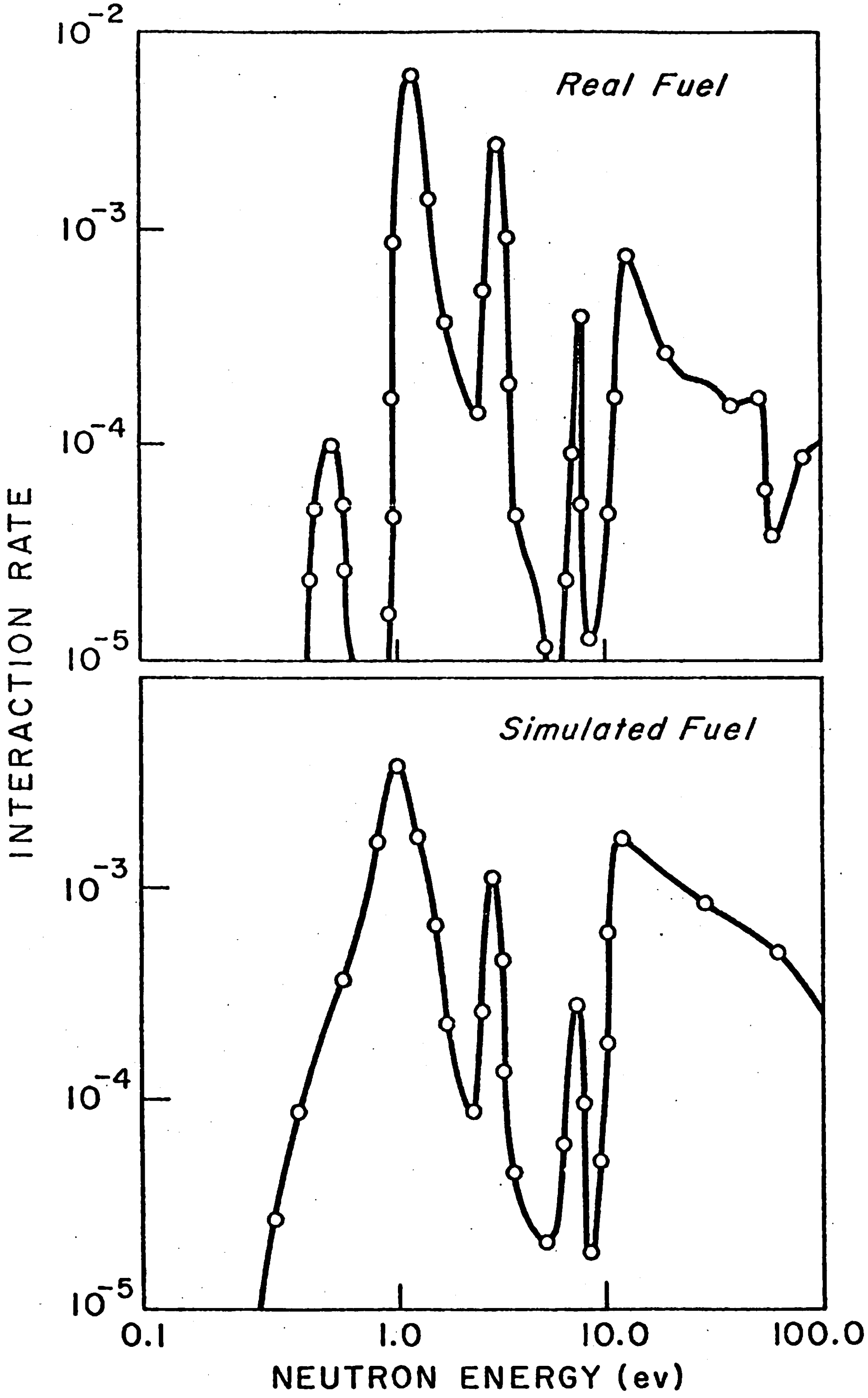


Figure 3

Comparison of Calculated Transmission Patterns Across a 217 Pin Bundle for Fine Angle Rotations Starting from 0°

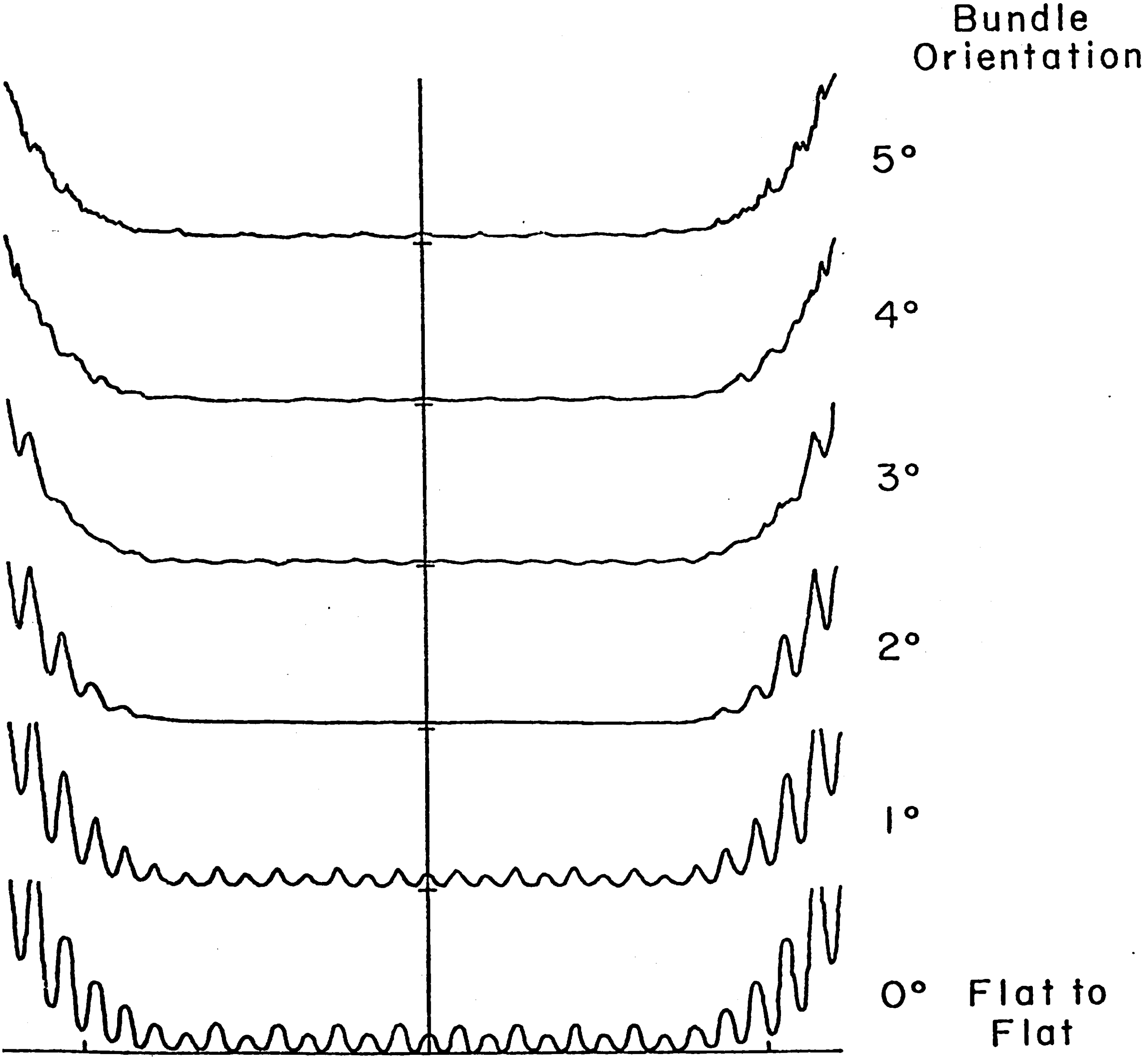


Figure 4

Computerized Axial Tomography Reconstruction From Theoretical Projections Across Typical Fuel Bundle Geometries

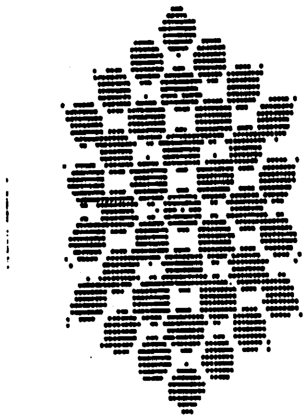


Fig 4 (a)

Data - 37 pin - No pellet gaps
Method - ART, No constraints
Angles - 17 (0° 170°x10° except 90°)
Iterations - 1
Pixels 85x85

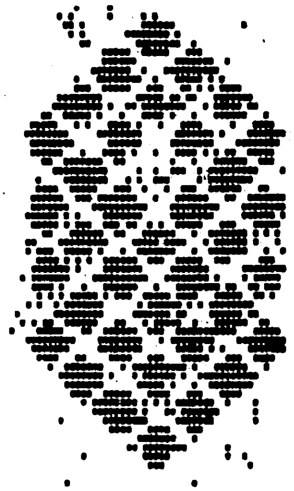


Fig 4 (b)

Data - 37 pin - One pellet gap
Method - ART with fuel/no fuel constraint
Angles - 4 (30°, 80°, 100°, 150°)
Iterations - 3
Pixels 63x63

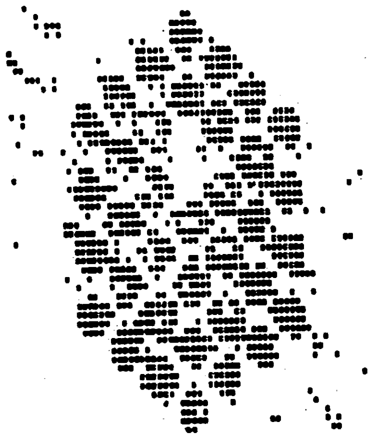


Fig 4 (c)

Data - 37 pin - One pellet gap
Method - ART with fuel/no fuel constraint
Angles - 17
Iterations - 3
Pixels 63x63

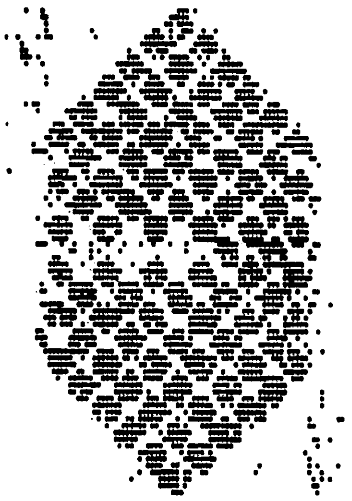


Fig 4 (d)

Data - 91 pin - Three pellet gaps
Method - ART with fuel/no fuel constraint
Angles - 17
Iterations - 3
Pixels 85x85

AN EXPERIMENTAL METHOD FOR THE DETERMINATION
OF L/D RATIO FOR NEUTRON RADIOGRAPHY SYSTEMS

J. C. Young, H. Harper, K. L. Crosbie and Joseph John
IRT Corporation, San Diego, California

SUMMARY

In actual operation of a neutron radiography system, the final resolution of a particular radiograph is dependent on the relative geometry of the system, the object being radiographed, and the film. The part of the resolution dependent on the system is essentially the effective solid angle subtended by the thermal neutron source at the film plane. In practice, the term L/D is often used to define this effective solid angle, where the source of effective diameter, D, is assumed to pass through a plane at some effective distance, L, from the film plane.

It often happens that the effective size and location of the source is quite different from those of the defining aperture. In such cases, the values of L/D computed from physical dimensions could be misleading. This is particularly significant in comparing the resolution capabilities of different systems. It is, therefore, very desirable that a technique be available for the determination of L/D by image analysis.

An experimental technique for the measurement of L/D ratios is proposed. Holes of various sizes are cut in a cadmium sheet, and radiographs are taken with the sheet located at different distances from the film plane. The sizes of resulting images are used to compute L/D ratio.

This technique was utilized to evaluate L/D ratios for two neutron radiographic systems manufactured by IRT Corporation. The results and conclusions will be discussed.

INDEX -- PART II