LA-UR- 98-3627

Approved for public release;
distribution is unlimited.

Title:

Assessment of Cold Neutron Radiography
Capability

Author(s):

Thomas E. McDonald, P-23

Joyce A. Roberts, LANSCE-12

Submitted to:

DOE OFFICE OF SCIENTIFIC AND TECHNICAL
INFORMATION (OSTI)

RECEIVED
MAY 03 1999
OSTI

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED *ph*

MASTER

Los Alamos
NATIONAL LABORATORY

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the University of California for the U.S. Department of Energy under contract W-7405-ENG-36. By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy. The Los Alamos National Laboratory strongly supports academic freedom and a researcher's right to publish; as an institution, however, the Laboratory does not endorse the viewpoint of a publication or guarantee its technical correctness.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Assessment of Cold Neutron Radiography Capability

Thomas E. McDonald, Jr.* and Joyce A. Roberts

Abstract

This is the final report of a one-year, Laboratory Directed Research and Development (LDRD) project at Los Alamos National Laboratory (LANL). Our goals were to demonstrate and assess cold neutron radiography techniques at the Los Alamos Neutron Science Center (LANSCE), Manual Lujan Neutron Scattering Center (Lujan Center), and to investigate potential applications of the capability. We have obtained images using film and an amorphous silicon detector. In addition, a new technique we have developed allows neutron radiographs to be made using only a narrow range of neutron energies. Employing this approach and the Bragg cut-off phenomena in certain materials, we have demonstrated material discrimination in radiography. We also demonstrated the imaging of cracks in a sample of a fire-set case that was supplied by Sandia National Laboratory, and we investigated whether the capability could be used to determine the extent of coking in jet engine nozzles. The LANSCE neutron radiography capability appears to have applications in the DOE stockpile maintenance and science-based stockpile stewardship (SBSS) programs, and in industry.

Background and Research Objectives

Radiography is the process of forming an image of an opaque specimen by shining a beam of radiation (e.g.; x-rays or neutrons) through it onto a photographic film or other position-sensitive detector. Cold neutron radiography (CNR) is an attractive technique in nondestructive testing and evaluation due to the strong energy variation of neutron cross sections. As a result of this strong variation, measurement of the intensity as a function of neutron energy and sample position can be used to give elemental and spatial information about an object. By using neutron energies in the millielectron volt (meV) regime, we can exploit an important behavior of the cross sections in crystalline materials.

*Principal Investigator, e-mail: mcdonald@lanl.gov

There is an abrupt change in the cross section when the wavelength of the neutron reaches twice the largest lattice spacing of the material, at which point the material becomes nearly transparent to neutrons. Materials with differing crystal structures can, therefore, be distinguished by carrying out radiography at specific neutron wavelengths (or energies). This behavior is generally not exploited in a reactor environment because the steady-state nature of the neutron source is not favorable to separating neutrons of different energies. In addition, this technique has the advantage over neutron thermal and resonance radiography by emphasizing the abrupt cross-section change rather than relying on the slower variation of cross section with thermal neutron energies or the presence of a useful neutron resonance cross section.

A cold neutron radiography instrument was established on flight path 11a at the Manuel Lujan Jr. Neutron Scattering Center (Lujan Center) for carrying out a proof-of-concept demonstration during the 1996-97 run cycle. We installed neutron guides on this flight path, which provided a pulse of neutrons having energies ranging down to a few tenths meV for use in radiography experiments. We used a scintillation detector with an intensified charged coupled device (CCD) imager that has the capability of precisely gating at any point in time along the pulse.

Such a capability allows, depending upon the materials, the radiography of separate materials in a device comprised of multiple materials. Thus, a device consisting of components of different materials such as aluminum, steel, copper, and carbon with possibly oil as a lubricant, all surrounded by a dense material such as lead or tungsten, could have each component radiographed separately through the dense material. The oil would also be imaged separately, which, for example, could allow verification of adequate lubrication in the assembled device. An even more dramatic possibility exists by using tomographic techniques to achieve three-dimensional images of individual components. The elements to assemble this capability currently exists at the Lujan Center together with the CCD intensified imaging technology that has been developed over the past years for the nuclear underground testing program.

Importance to LANL's Science and Technology Base and National R&D Needs

To date, the majority of cold neutron radiography work has been conducted at reactors where the steady-state source of neutrons does not allow for range of energy (wavelength) scanning that is accessible at a pulsed source. By developing this program, we will broaden the Los Alamos technology base for interactions with industry and academia. This project enhances the Laboratory capability in materials by adding a

component of failure analysis, particularly in systems employing hydrogen (e.g., fuel cells) or hydrocarbons (e.g., jet engines). By better understanding the flow of lubricants or the coking of jet nozzles, better predictions of component lifetimes will result. In addition, this project will complement the x-ray radiography that is currently employed in the Science-based Stockpile Stewardship (SBSS) program by providing a technique of imaging through dense materials, which x-rays cannot penetrate.

Scientific Approach and Accomplishments

Basic Concept of Time-Gated Energy-Selected Neutron Radiography

The basic concept for carrying out neutron radiography using only a narrow range of neutron energies, which we refer to as Time-Gated Energy-Selected (TGES) neutron radiography, is illustrated in Figure 1. A short neutron pulse is formed at the beginning of the flight path at time t_0 . The pulse travels to the end of the flight path where the more energetic (faster) neutrons arrive at early times and the lower energy (slower) neutrons arrive at later times. The arrival time of neutrons at the end of the flight path is proportional to the inverse of the square root of the neutron energy. The object to be radiographed and imager are positioned at the end of the flight path to record the radiographic data. The gate (shutter) width, t_g , of the imager is adjusted to record the radiographic data from a range of neutron energies. This is done by adjusting the gate opening to occur at the time of arrival at the sample of the highest energy neutrons to be used in making the radiograph, and by adjusting the closing time to occur at the time of arrival of the lowest energy neutrons. The time from t_0 to the gate opening, which is the travel time along the flight path of the highest energy neutrons making the radiograph, is referred to as the gate delay time, ΔT . This technique, for which we have submitted a patent disclosure, was first demonstrated at the Lujan Center.

CNR Experiment Facility

A time-gated, energy-selected, radiography capability was installed on beam line 11a of the Lujan Center at LANSCE. This beam line shares a common shutter assembly with beam line 11b. The accelerator, through a pulse storage ring, delivers an 800-MeV proton pulse (pulse width approximately 270 ns) to a split spallation tungsten target at a rate of 20 pulses per second. The resulting neutron pulse is moderated by a liquid hydrogen moderator to produce a neutron pulse having a relatively large distribution of cold neutrons; that is, neutron energies in the region of a few millielectron volts, which are in the energy range (1 to 10 meV) of the Bragg cutoff of many materials (Ref. 1). A small percentage of

these neutrons enter the flight path 11a beam guide, which penetrates the biological shield, and are transported to a shielded room where the radiography is carried out. The total length of the flight path from the spallation target to the end of the beam guide in the shielded room experimental area is approximately 19.5 m.

The beam guides were purchased from the French company, Cilas. The guides come in 1.5-m sections, have a square aperture 6 cm on a side, and are coated with nickel-58 to enhance neutron reflection. The critical angle, which is the largest angle from the guide center line that will be reflected by the nickel-58 coating, is energy dependent. Thus, the beam divergence, which directly affects the resolution of a radiograph, depends upon neutron energy. Guide stands and shielding were designed and installed by Los Alamos. Flight times for the 19.5-m path length of various neutron energies (and corresponding wavelengths) and critical angles in the energy range of interest are given in Table A.

Gated Imaging System

The gated imaging system used on FP 11a consisted of a scintillator on which an image is formed, a mirror placed at a 45-degree angle next to the scintillator to relay the image out of the beam path, and a lens to focus the image onto an intensified, cooled CCD

Table A
Neutron Parameters in LANSCE CNR Radiography Facility

Neutron Energy (meV)	Wavelength (angstroms)	Flight Time (ms)	Critical Angle (degrees)
1	9.0	45.0	1.03
2	6.4	31.8	0.73
4	4.5	22.5	0.51
8	3.2	15.9	0.36
16	2.2	11.2	0.26
32	1.6	7.9	0.18

camera. The relay mirror is necessary due to the damage that would occur to the CCD sensor if placed in the neutron beam. The lens is used to set the field of view and, thus, the resolution of the system. The intensifier is used to amplify the low light level from the scintillator and also serves as a gate, or shutter, for the camera. A schematic diagram of the imaging system is shown in Figure 2.

The scintillator screen used in the imaging system is a commercial product, BC704, which is available from the Bicron facility in Newbury, Ohio. The scintillator material is

based on ZnS(Ag) and ^6Li (Ref. 2). The wavelength of maximum emission is in the blue at 450 nm. The light-emission decay time is approximately 200 ns, which is more than adequate for the 100 μs and longer gate time used in the experiments. The absolute scintillation efficiency is approximately 9%. Each thermal neutron stopped by the scintillator produces 1.75×10^5 photons. Two configurations of the scintillator screen are available from the manufacturer, a standard screen mounted on a 1-mm thick aluminum plate and an unmounted, semi-rigid, stand-alone screen. The unmounted configuration was used in these experiments. The resolution of the scintillator screen has been reported to be 50 microns (Ref. 3).

A 40-mm intensifier was used in the imager. The pixel array size of the CCD in the camera was 1024×1024 and had a pixel size of 24 microns on a side. A 200-mm f/2 lens was used to focus the image onto the intensifier and dimensions were set to achieve a field of view of approximately 2.1 cm, which, by calculation, is a resolution of approximately 21 line-pairs per mm. Using an Air Force resolution pattern we measured a resolution of approximately 20 line-pairs/mm of the lens, intensifier, and camera combination, which is in close agreement with calculation. This system resolution would allow features as small as 50 to 100 microns to be visible.

Control of the imager is accomplished in a straightforward manner with digital delay and pulse generators. An intensifier control unit supplied the intensifier gain voltage and gate pulse. Camera control was accomplished with a separate camera control unit, which monitored camera operation and performed frame readout and storage. A block diagram of the timing and control setup is shown in Figure 3. The intensifier gate width from the intensifier control unit ranges from 10 microseconds to 1.8 ms, which is an adequate range for the gated neutron radiography.

Radiography Results

We carried out radiography on test components using three imaging techniques, the TGES radiography system described above, an amorphous silicon detector, and conventional x-ray film. Materials discrimination using time-gated imaging was demonstrated for the first time at LANSCE and we demonstrated that relatively high resolution imaging could be obtained using both the amorphous silicon detector and conventional x-ray film. We radiographed a Sandia-supplied test sample of a cracked fire-set case to determine if such cracks could be imaged with neutron radiography; we obtained radiographs clearly showing the crack with a resolution estimated to be between 5 and 10 microns.

In a collaboration with the Phoenix Memorial Laboratory at the University of Michigan, we radiographed two jet engine nozzles to determine if coking could be observed in the nozzles. This test demonstrated that higher resolution would be needed in the beam line to observe the small amounts of coking in these nozzles.

Time-Gated Energy-Selected Cold Neutron Radiography

One of the demonstrations of this technique on FP11a was carried out using two materials that have well-defined Bragg cutoffs: beryllium, which has a Bragg cutoff at approximately 6 meV, and carbon, which has a cutoff at approximately 1.9 meV. A 25-mm thick beryllium block was obtained into which a one-half by 20 threaded hole was cut (one-half inch diameter and 20 threads per inch). A one-half by 20 carbon screw was inserted into the hole. Radiographs were made above, between, and below the two Bragg cutoffs.

The results of the radiography are shown in Figure 4. Figure 4A shows a radiograph taken at approximately 7.5 meV, which is above the Bragg cutoffs of beryllium and carbon. Above the Bragg cutoffs both the beryllium and carbon show up relatively dark in the radiograph because the scattering cross sections are high. The portion of the carbon bolt inside the beryllium cannot be observed. Figure 4B shows a radiograph taken at approximately 2.9 meV, which is between the Bragg cutoffs of the two materials, and the beryllium has become much lighter because the scattering cross section has significantly decreased while the carbon bolt remains relatively dark. That portion of the carbon inside the beryllium has now become visible. Figure 4C shows a radiograph taken at approximately 1.5 meV, which is below the Bragg cutoff of both materials, and both materials have become light in the radiograph and that portion of the carbon in the beryllium is no longer visible. Although this phenomena is material dependent and is not exhibited for all materials, we believe there are enough materials, such as carbon and iron, for which an abrupt change is exhibited that the approach can be exploited in programs of interest.

Radiography Using an Amorphous Silicon Detector

Use of an amorphous silicon detector was also demonstrated on the 11a beam line. The advantage of the amorphous silicon detector is that, unlike a CCD silicon detector, it can be placed directly in the neutron beam path with effectively no damage if the beam is not left on the detector for long periods of time. Thus, there is no need to relay the image using optics and a good quality image (tens of microns) can be obtained relatively quickly (within a few seconds). To obtain the image, a Bicron 704 scintillator was placed flat against the amorphous silicon detector. Unfortunately, the amorphous silicon detector

cannot be gated and, therefore, cannot be used for the TGES technique. Figure 5 is an example of an image we obtained with a Reticon amorphous silicon detector, which shows the high quality that can be obtained with such a detector. One can also observe a nylon washer inside a brass fixture in the image, which is a classic example of imaging a low-density material inside a high-density material with neutron radiography. If one were carrying out radiography with x-rays, the nylon washer would not be observed in the image.

Radiographs with X-ray Film

The highest quality and resolution radiographs we obtained were achieved with x-ray film. A thin gadolinium foil is placed next to the film and produces x-rays proportional to the local neutron flux. The x-rays expose the film. Figure 6 shows a radiograph of a cracked fire-set sample provided by Sandia. We estimate the resolution of this radiograph to be between 5 and 10 microns. As with the amorphous silicon detector, gated imaging cannot be obtained with the film technique.

Coking in Jet Engine Nozzles

An important problem in industry (as well as the military) is the buildup of hydrocarbon solids in jet engine nozzles, which is referred to as coking. Coking leads to a number of combustion and maintenance problems in jet engines and being able to observe and analyze coking is important to manufacturers. X-ray radiography cannot be used to observe coking because the hydrocarbon buildup is a low-density material contained by the body of the nozzle, which typically consists of high-density materials such as stainless steel and titanium alloys. However, the configuration of low-density material inside a high-density material is particularly well suited for neutron radiography. This issue was brought to our attention by John Lindsay of the Phoenix Memorial Laboratory, University of Michigan (Ref. 4), who provided two coked nozzles for radiography on our facility. He also visited our facility to observe the procedure and provide advice based on his extensive experience in neutron radiography.

We radiographed both nozzles using the gated imager, the amorphous silicon detector, and x-ray film. Because results were similar for both nozzles the results from only one of the nozzles will be presented in this report. A photograph of the nozzle is shown in Figure 7. The nozzle is approximately 15 cm in overall length with the “head” approximately 1 cm in diameter and 2-cm long. The “neck” is approximately 7 mm in diameter.

The first radiograph of the nozzle was made with the gated imager using the TGES technique because the low energy (long wavelength) neutrons have a large scattering cross-section relative to the nozzle body at low energies. A radiograph taken with the gated imaging technique is shown in Figure 8. This image represents the highest resolution gated imaging radiograph that could be obtained with the TGES imager, which unfortunately does not reveal the coking. This radiograph is estimated to have a resolution of 100 to 200 microns, which is almost two orders of magnitude lower than would be required to observe the coking. Resolutions approaching one micron would be needed to observe the coking in these nozzles.

To obtain radiographs at higher resolution we used the amorphous silicon detector and x-ray film. Although the resolution of the amorphous silicon detector and x-ray film radiographs are estimated to be 20 to 40 microns (film radiograph has a somewhat higher resolution than the amorphous silicon detector radiograph), both are still too low to observe the coking. The primary source of the low resolution in these radiographs is the beam divergence coupled with the fact that the geometry of the nozzles does not allow a flat placement against the detector or scintillator. The nozzle is located approximately 3 to 4 cm away from the detector.

Interactions

In order to inform potential industrial users of the cold neutron radiography capability at LANSCE and to begin identifying potential industrial applications and to assess interest in the capability by industry, we gave presentations, held discussions, attended conferences and began establishing interactions with industrial neutron radiography experts. Interactions were established with John T Lindsay of the Phoenix Memorial Laboratory, University of Michigan, who provided us with two jet engine nozzles to assess the potential of the LANSCE cold-neutron radiography facility to image coking (see above). He also visited the facility to observe our operation, briefed us on potential industrial applications, and suggested improvements for the beam line.

Talks and presentations we have made include the following 1) presentation at American Society for Metals meeting in Cincinnati and at the University of Cincinnati, 2) poster paper at LANSCE Users Group Meeting at which members of the radiography community were present, 3) presentation at 5th Scientific Symposium on Room Temperature X-Ray, Gamma-Ray, and Neutron Detectors, Sandia National Laboratories at Livermore and 4) presentation at the Weapons Agency Nondestructive Testing Organization meeting at Los Alamos. In addition, discussions were held with several industry representatives at the International Conference on Neutron Scattering in Toronto. Much

interest has been expressed in the LANSCE cold-neutron radiography capability at these meetings and conferences and some follow-on discussions have resulted. We expect interest in the capability to grow as we continue to inform and interact with the neutron radiography user community in industry.

Possible Applications

The use of cold and thermal neutron radiography appears to have applications in both industry and the DOE stockpile maintenance programs. These potential applications are discussed below.

Industrial Applications

We have currently identified two potential industrial applications. One is to determine the extent of coking in jet engine fuel nozzles, which was discussed above. This particular application appears to be well suited for cold or thermal neutron radiography because it involves imaging a light material within a heavy material. X-ray radiography cannot be used for this application. However, our initial attempts to radiograph nozzles demonstrated that improvements are needed in the resolution of the beam line. We are considering possible approaches to making such improvements. A second application is determining nonuniformities and inhomogeneities in a sheet of polymer material that has recently been developed by an industrial firm. Although only two industrial applications have been identified, we believe many more exist and we plan to continue to aggressively identify and test additional applications of interest to industry.

Weapons Stockpile Surveillance-Related Applications

Several potential applications have been identified in the weapons stockpile surveillance area. The first application involves determining the water content in desiccant. Oak Ridge National Laboratory (ORNL) has provided a mock device for testing this concept, which we plan to radiograph during the next run cycle. A second application is the determination of electrical breakdown paths in failed lead-barium-zirconate-titanate (PZT) ceramic electrical generators that are used in some weapons-related applications. Sandia fabricates these generators and when failures occur it is difficult to diagnose the cause. The PZT ceramic is encapsulated and the breakdown path is within the encapsulant; physically opening the device disrupts the breakdown path and prevents an effective cause analysis. Sandia has asked if we could obtain a radiograph of the breakdown track in a failed device to assist with determining cause of failure.

A third application is the study of gas flow in a gas handling apparatus. Because of the pulsed beam at LANSCE we may be able to study the dynamics of the gas flow in the device. A fourth application is the determination of voids and defects in detonators. A fifth application involves determining the uniformity of materials in a fire-set case for Sandia. The case is fabricated from epoxy reinforced with borated glass fibers. It is approximately 5-mm thick and 45 cm in diameter. We have demonstrated that a crack in the material can be observed with good resolution and we are optimistic that CNR can also be used to observe inhomogeneities in the material make up.

The sixth application, which is more uncertain than those previously mentioned, involves the radiography of bulk material assemblies to identify possible anomalies and defects in the assembled materials. Because the bulk assemblies have relatively high mass, we are somewhat skeptical that effective radiography can be carried out on beam line 11a and we plan to first study this application through simulation.

Continued Assessment

We will continue to identify potential applications for LANSCE cold and thermal neutron radiography capability. For example, CNR is an excellent method for imaging hydrogenous materials such as water or oil inside metallic containers. Because the neutrons have wavelengths beyond the Bragg cutoff of the metal, they penetrate deeply without being scattered. The strong incoherent scattering by hydrogen then provides the contrast required for the radiographic technique to work. This method has been used successfully to image lubricants in operating engines, to find water inside a metal container, and to detect hydrogen in aircraft wings before it reaches a concentration that may cause embrittlement. One of the goals of future assessments would be to examine such applications, interact with potential sponsoring industries, and identify the most promising application, both from a technical and programmatic/funding viewpoint. We also plan to employ tomographic reconstruction techniques to achieve three-dimensional images of components.

In summary, potential applications that we have identified at the present time are listed below.

Industry-Related

- Extent of coking in jet engine nozzles
- Nonuniformities and inhomogeneities in sheet material

Weapons-Related

- Water content in desiccant (mock assembly from ORNL)
- PZT electrical generators breakdown track
- Dynamic gas flow in gas assemblies
- Detonator defects
- Fire-set case inhomogeneities
- Bulk assembly anomalies and defects
 - Moisture content
 - Cracks
 - Movement

Conclusions and Future Directions

The cold neutron radiography capability at LANSCE can achieve static results comparable to other more established radiography facilities around the world. High quality radiographs can be produced with a CCD imager or an amorphous silicon imager in a matter of minutes and with film in essentially the length of time required for film developing. An advantage to the LANSCE beam is the lack of a high flux of gamma rays, which are generally present in reactor radiographic facilities. In addition, a new and unique capability to radiograph at specific energies has been established at the facility, which is possible because of the pulsed nature of the source. We plan to continue to characterize this new capability and assess uses and applications.

Additional improvements in the quality of the radiographs can be made by reducing the divergence of the beam. With the improved beam divergence that is possible on the facility, radiography having a resolution in the region of 1 to 5 microns is expected to be feasible.

References

1. Pynn, R. , "Neutron Scattering: A Primer," Los Alamos National Laboratory Report, LAUR-95-3840.
2. A. R. Spowart, "Optimizing Neutron Scintillators for Neutron Radiography," British Journal of Non-Destructive Testing, **11(1)**, 2-11, March 1969.
3. S. Fujine, et al., "An On-line video Image Processing System for Real-time Neutron radiography," Nucl. Inst. & Meth., **215**, 277-289, 1983.
3. J. T. Lindsay, et al., "Coking determination in gas turbine engine nozzles using neutron radiography," Proceedings of the 5th World conference on Neutron Radiography, Berlin, Germany, June 1996.

Acknowledgments

The authors would like to acknowledge and thank the following people for their work on and assistance with this project: Torben Brun, Thomas Claytor, Eugene Farnum, Robert Gallegos, Geoffrey Greene, Lloyd Hunt, Steven Jaramillo, Nicholas King, Wilfred Lewis, Christopher Morris, Russel Mortensen, Peter Pazuchanics, Susan Seestrom, and William Teasdale.

Figure 2. Diagram of cold neutron radiography gated imager. The object to be radiographed is placed in the beam in front of the scintillator. The image is formed on the scintillator and relayed by mirror and lens to the intensified camera. The mirror is necessary because of damage that would occur to the CCD if placed in the neutron beam. The lens defines the field of view and resolution of the image and the intensifier provides amplification of the low light levels from the scintillator and also serves as a gate (or shutter) for the camera.

Figure 3. Imaging-system control block diagram.

Figure 4A

Neutron Energy: 7.5 meV
Above Cutoff of Be (6 meV)
Above Cutoff of C (2 meV)
Both Be and C Dark

Figure 4B

Neutron Energy: 2.9 meV
Below Cutoff of Be
Above Cutoff of C
Be Light; C Dark

Figure 4C

Neutron Energy: 1.5 meV
Below Cutoff both Be and C
Both Be and C Light

Figure 4. Demonstration of cold neutron radiography using time-of-flight and gated imaging to obtain radiographs at specific neutron energies.

Figure 5. Neutron radiograph taken with a Reticon amorphous silicon detector. The sample is a 25-mm-thick beryllium block with threaded holes (20 threads per inch) into which are screwed a nylon screw (left) and a brass fitting (right). An aluminum nut has been fully screwed onto the nylon screw and can be seen abutting the screw head. Also seen in the image is a nylon o-ring inside the brass fitting. Such an o-ring would not be visible in a x-ray radiograph. The resolution of this neutron radiograph is approximately 150 microns. The dark vertical lines in the image are columns of defective pixels in the detector.

Figure 6. This image is an example of the highest resolution radiography that has been achieved on the LANSCE CNR facility. The image is a radiograph of a cracked fire-set case sample provided by Sandia. The radiograph is an experiment to determine if such a crack could be imaged by neutron radiography. The crack is well defined in the radiograph with a resolution estimated to be in the neighborhood of 10 microns. The radiograph was obtained with x-ray film; a thin foil of gadolinium was placed next to the film to serve as a neutron to x-ray converter.

Figure 7. Photograph of jet engine nozzle that was radiographed to determine coking buildup.