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Review and Evaluation of Technology, Equipment, Codes and Standards for Digitization of Industrial Radiographic Film

U.S. Nuclear Regulatory Commission

Task Group on Digitization of Industrial Radiographs

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ABSTRACT

This report contains a review and evaluation of the technology, equipment, and codes and standards related to the digitization of industrial radiographic film. The report presents recommendations and equipment performance specifications that will allow the digitization of radiographic film from nuclear power plant components in order to produce faithful reproductions of flaw images of interest on the films. Justification for the specifications selected are provided. Performance demonstration tests for the digitization process are required and criteria for such tests is presented. Also several comments related to implementation of the technology are presented and discussed.

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EXECUTIVE SUMMARY

This report, written by the Nuclear Regulatory Commission Task Group on Digitization of Industrial Radiographs, contains a review and evaluation of the technology, equipment, and codes and standards related to the digitization of industrial radiographic film. The report presents recommendations and equipment-performance specifications that will allow the digitization of radiographic film from nuclear power plant components in order to produce faithful reproductions of the images on the films.

The basis for radiography of components contained in nuclear power plants is the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section V, Article 2 and Article 22 (the section containing the accepted American Society for Testing and Materials [ASTM] standards). Article 2 of ASME Section V establishes the minimum requirements for radiography. The requirements in these codes that are important to digitization are the parameters establishing the actual image recorded by the radiograph. These are optical density, image quality indicator, and geometric unsharpness. For radiographs of nuclear power plant components, optical densities (ODs) of 1.0 to 4.5 must be digitized. Film digitization is a relatively new technology and there are few standards for the digitization of radiographs. However, the ASME Section V Appendix III document on digital image methods for radiography and radioscopy addresses this issue. This recent document outlines in very broad terms the requirements for digitizing radiographs.

For faithful image reproduction (in terms of equal performance for a film interpreter), the digitization system should be capable of displaying density variations as small as 0.01 OD and features as small as 100 μm. Theoretical and experimental considerations leading to these values are presented in this report.

Four basic parameters determine system performance: (1) digitizing spatial resolution (DSR) (i.e., pixel size or spacing); (2) dynamic range; (3) digital fidelity (e.g., 12 bits); and (4) minimum detectable film density change. DSR is the determining factor in the system's spatial-resolution limits. The minimum detectable film density change is dependent upon digital fidelity and noise level. All of these performance factors may be characterized as a single function known as the modulation transfer function (MTF). The MTF should be used as a measure of system performance and a recommended procedure for this measurement is described in the report. We determined that at 5 line pairs per millimeter (lp/mm), an MTF of 0.33 will be required to detect a 100-μm feature with a contrast sensitivity of 0.01 OD. In addition, a 12-bit system with a signal-to-noise ratio of at least 2000:1 at 2.0 OD and 300:1 at 3.5 OD is required. Data storage will require write-once/read-many technology. Standards must be developed to qualify and monitor system performance. Image processing should be carried out by qualified personnel and must not lead to the loss of data acquired in the initial digitization. All of the above represent minimum acceptable requirements.

The state-of-the-art equipment available in today's market seems capable of providing digital copies of existing radiographs that are essentially identical to the originals. In fact, most digitization techniques provide some slight improvement in the readability of the digital image over the original through enhancement techniques. For example, the digitization process provides an averaging of the density variations in small areas of the film. This improves the signal-to-noise ratio of the image as interpreted by the eye. The main goal in image enhancement is to accentuate certain often- subtle image features for subsequent analysis or display. The enhancement process itself does not increase the inherent information content in the data. Enhancement does, however, increase the visibility of the chosen features so that they can be detected more readily.

Storage of the digitized image on write-once-read-many optical discs or their equal and lossless compression of the data will assure that no valuable records are lost. Life-time of the optical disc storage is anticipated to be up to 100 years.

As a result of its experiments and evaluations, the task group feels there is a need for personnel with both radiographic interpretation skills and digitizing equipment operation skills in order to produce quality archived radiographic images. These personnel should be skilled in the proper selection and use of image processing techniques and in interpreting and analyzing of the digitized radiographic images. Furthermore, equipment meeting minimum specifications and capable procedures need to be used by qualified personnel in order to develop faithful digital images of flaw indications of interest on the radiographic films. Therefore, a performance demonstration test for qualification of the digitization process which includes the personnel, procedures and equipment is required.

Although we have cited in this report a number of standards related to film digitization it is our opinion that no existing standard specifies the minimum capability for a radiographic digitization system.

Only "Code Acceptable" radiographs should be digitized and stored as the official plant record. Digitization of radiographic film is not intended to be a means of improving for acceptance an unacceptable radiograph.

Generic Letter 88-18, Plant Record Storage on Optical Disks, dated October 20, 1988, provides an acceptable framework for the storage of digitized radiographic images.

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LIST OF DEFINITIONS AND NOMENCLATURE

Aliasing—Introduction of error into the reconstructed image because the sampling interval does not allow the proper representation of higher frequency information.

ASME—American Society of Mechanical Engineers

ASTM—American Society for Testing and Materials

CCD (Charge-Coupled Device)—A semiconductor device wherein minority charge is stored in a spatially defined depletion region at the surface of a semiconductor and is moved about the surface by transferring this charge to similar regions.

Contrast Sensitivity—The smallest contrast of brightness that is perceptible to the human eye under specified conditions.

Data Compression—The technique of reducing the number of binary digits required to represent data.

Digital Filter—An electrical filter that responds to an input which has been quantified, usually as pulses.

DSR—Digital spatial resolution

Dynamic Range—The ratio of the specified maximum signal level capability of a system to its noise level.

EPS—Equivalent penetrameter sensitivity

Film Unsharpness—Inherent unsharpness of the radiographic film. It is one of the elements of unsharpness in high-energy radiography and increases with increasing radiation energy and film grain size.

Geometric Unsharpness—Unsharpness in a radiograph defined by the expression $U_g = F/(D/t)$ where F is the focal spot size, D is the distance from the focal spot to the front surface of the object being radiographed and t is the thickness of the object or the distance from the front surface of the object to the film.

IQI—Image quality indicator

Interlaced Scanning—Process in which the distance from center to center of successively scanned lines is two or more times the nominal line width, so that adjacent lines belong to different fields.

(MTF) Modulation Transfer Function—A relationship which describes the ability of a system to render detail as a function of the spatial frequency of the subject. It is defined as the ratio of the image amplitude to the object amplitude as a function of the spatial frequency of the object. For film digitization systems, it can best be approximated using a pattern of alternating light and dark bars which get progressively finer. At very low spatial frequencies, the system fully images the light and dark bars and full modulation is achieved. As the spatial frequency of the light and dark bars increases, the blurring introduced by the imaging system will result in a loss of contrast between the light and dark areas. In the extreme, the imaging system will no longer be capable of resolving the light and dark bars and the image produced will be a uniform medium gray. The MTF for an imaging system is then expressed as a curve relating the image contrast produced (in percent of full modulation) to the spatial frequency of the input pattern. It is usually specified as a contrast level at a given spatial frequency (in line pairs per millimeter [lp/mm]).

OD (Optical Density)—The degree of opacity of the radiographic film expressed by Log (I_o/I) where I_o is the intensity of the incident ray and I is the intensity of the transmitted ray.

Penetrameter (Image Quality Indicator)—Device used to indicate the quality of a radiograph. In one type, quality is judged by checking for the discernability of certain holes in a thin plaque or from the outline of the plaque itself. Customarily, because many codes are so phrased, the plaque thickness (T) will be 2% of the weld thickness, and visibility on the radiograph of a hole whose diameter is two times the plaque thickness (2T) will be required. A wire type of penetrameter can also be used. Customarily, at least two thirds of the significant wire length should be resolved on the film. The wire diameters vary.

Pixel—The smallest part of electronically coded picture image. The smallest addressable element in an electronic display.

Refresh Rate—Rate at which one periodically replaces data to prevent the data from decaying.

Signal-to-Noise Ratio (SNR or S/R)—The ratio of amplitude of a desired signal at any point to the amplitude of noise signals at that same point.

Windowing—The process of selecting, from the data of a digitized image, a limited range of the total dynamic range available and presenting it on the monitor. It may not be possible to show the entire dynamic range acquired in the digitization process, if for example, the data acquisition system is 12 bits (4096 levels of gray) and the image presentation is 8 bits (255 levels of gray).

WORM—Write-once/read-many device for data storage.

1 INTRODUCTION

Radiographic information is crucial in ensuring the quality of construction and the structural integrity of nuclear power plants. Radiographic film can capture the needed flaw information from the many materials and components found in a nuclear power plant. Codes require that specific records be kept for the lifetime of the plant, and the radiographic films are part of these mandated records. It is imperative that this information be both unaltered and quickly retrievable for at least the life of the plant. However, radiographic films are known to degrade with time; therefore, information may be altered and/or destroyed, and furthermore, the large volume of radiographs at a plant makes retrieval difficult. Recent technology may be able to overcome these problems.

Recently developed technology permits the digitization of industrial radiographic films. Because of the problems mentioned above, the nuclear industry is interested in using this technology; therefore, the Office of the Executive Director for Operations of the Nuclear Regulatory Commission (NRC) has requested that a technical position on the digitization of radiographic films be developed. In response to this request an action plan was developed. A task group was formed to review and evaluate the technology, related codes and standards,[1-12] and technical issues.

This task group consisted of personnel from the NRC (headquarters and regional offices), national laboratories, and industry who have expertise in radiography, codes and standards, signal processing, and qualification processes for nondestructive testing. The task group followed the developed action plan and met to plan activities and conduct interactive technical discussions and evaluations, visited vendors of equipment for digitizing radiographic film, conducted literature searches, performed experiments, and prepared this document.

A major advantage of digitizing radiographic films is that archived radiographs in digital form can eliminate further degradation of data in the existing films due to aging. Therefore, the original films can be discarded or recycled, resulting in a savings of space and storage costs. Furthermore, digitizing provides easy management of the data and access to the data from multiple sites through electronic means. The digitized radiograph can take advantage of image enhancement techniques that may make a discontinuity more readily visible to confirm its presence and/or determine its extent.

Because radiographic film degrades over time, many films may not remain acceptable throughout the anticipated 40-year life of the facility and beyond. Thus, digitization and storage of radiographic films may be considered desirable by the industry to support a request for license renewal and ensure that the quality of the information is maintained during the extended life of the plant.

This report contains (1) technical specifications for the digitization of radiographic film to faithfully reproduce the radiographic image; (2) a review of background information, including codes and standards for the radiographic examination of nuclear power plant components; (3) the technical basis and justification for the equipment performance parameters recommended; (4) a review and evaluation of existing equipment, technology, and codes and standards for the digitization of radiographic film images; (5) a discussion of implementation issues, including performance demonstration for personnel using digital imaging systems; (6) recommendations and conclusions; and (7) an executive summary.

2 TECHNICAL BASIS

In this section, the codes for radiography of nuclear plant components will be reviewed and standards relevant to the digitization of radiographs will be discussed. Determination of the minimum size of an indication to be imaged, as estimated from open-literature publications and experiments by the task group, will be presented. Finally, the specifications of a system capable of digitizing radiographs with the necessary contrast sensitivity and resolution will be discussed.

2.1 Review of Relevant Codes for Radiography of Nuclear Power Plant Components

The codes applicable to radiography of components contained in nuclear power plants currently operational or under construction in the United States are the American National Standards Institute (ANSI) B31.1, ANSI N31.7 code and the ASME Code. ANSI B31.1 is the applicable construction code for piping components of plants constructed before the ASME Code took responsibility. Some plants were constructed under the ANSI N31.7 code for piping components. This was a code formulated specifically for nuclear power plants and also preceded the ASME Code. Most plants fall directly under the jurisdiction of the ASME Code. In most cases, the radiography of welds was done in accordance with ASME Section V. Specific ASTM standards are referenced for guidance by ASME.

Thus, the basis for weld radiography in nuclear power plants, for the most part, is ASME Section V, Article 2 and Article 22 (the section containing the accepted

ASTM standards). Article 2 of ASME Section V establishes the minimum requirements for radiography. The requirements important to digitization are the parameters establishing the actual image recorded by the radiograph. These are optical density, image quality indicator, and geometric unsharpness.

The ASTM standard [illegible] nce radiographs for steel welds[2] is clearly pe[illegible] because it permits the establishment of types and severities of discontinuities encountered in steel weldments. The ASTM standard that describes radiographic inspection of welds is also cited.[3] The scope of this method standard "provides a uniform procedure for radiographic examination of weldments ..."

2.1.1 Optical Density

For single-film viewing, the optical density (OD) of a radiograph produced by X-rays may be no less than 1.8 when measured through the body of a plaque penetrameter or when measured immediately adjacent to a wire penetrameter and in the area of interest. The minimum OD for a radiograph produced for single-film viewing with an isotope is 2.0. The minimum for a single film when used in composite viewing is currently 1.3, regardless of the radiation source. Some earlier versions of the ASME Code permitted individual films of a composite series to have optical densities as low as 1.2. It is relatively common to stack multiple films in order to obtain acceptable optical density over the full area of interest. The maximum OD in all cases is 4.0. A tolerance of 0.05 OD is allowed for variations between densitometer readings.

In addition to these overall density limits, the penetrameter density must be within -15% and +30% of the density in the area of interest. In later editions of the ASME Code, the upper limit can be exceeded if shims are used and the required sensitivity is maintained. Multiple penetrameters are often placed on a single film to cover variations in optical density; this ensures the quality of the area of interest.

2.1.2 Image Quality Indicators

The image quality indicator (IQI) is used to ensure that some minimum image quality is obtained. It is not a direct indication of the minimum flaw size that can be revealed in a radiographic exposure. A popular misconception stems from the comparison between the minimum detectable hole in the penetrameter and the minimum detectable indication in the object being radiographed. Since the issuance of the 1986 edition of ASME Code Section V, two distinct and very different IQIs have been available for radiography: the plaque penetrameter IQI and the wire IQI.

The plaque penetrameter is the first and still the most popular image quality indicator in use. The plaque thickness is 2% of the thickness of the object in the area of interest. For purposes of the ASME Code, the applicable object thickness for a welded structure is the base material thickness. For radiographs of castings, the IQI thickness is based on the end-product thickness of the casting.

The plaque penetrameter contains three holes. For radiographs of ASME Section III Subsection NB components taken in the early 1980s, the penetrameter includes a slot. Diameters of the three holes are 1, 2, and 4 times the plaque opthickness. The quality of the radiographic image is defined by the combination of the IQI thickness used and the minimum hole that must be seen by the radiographic interpreter. In ASME codes, only two quality levels are generally specified, 2-2T or 2-4T. This indicates a penetrameter of 2% thickness (2-) with the minimum visible hole 2 times penetrameter thickness (2T) or 4 times the penetrameter thickness (4T). For more difficult radiographic applications, the Code affords the radiographer greater latitude by requiring only a 2-4T quality level.

Relatively new in the ASME code is the use of wire penetrameters, which is allowed through acceptance of the ASTM standard for wire penetrameters ASTM E 747.[5] That document describes a series of four wire IQIs that apply to material thicknesses up to 20 in. Each IQI is a plastic envelope that contains a series of wires. These wires are equivalent to the combination of plaque thickness and penetrameter hole as an indicator of radiographic quality. The quality level designation when using the wire IQI is the IQI identification and wire size that must be shown. This type of IQI has been specified for many years in the Deutsche Industry Norm (DIN) standard used in Germany.

2.1.3 Geometric Unsharpness

The geometric unsharpness is the blurring of the radiographic image caused by the fact that the radiation source has a finite size. It is dependent on the physical size of the radiation source, as viewed from the film location, and the ratio of the part thickness to the distance between the source and the part. The geometric unsharpness is limited by most radiography codes and standards to control the amount of blurring so produced. The ASME Boiler and Pressure Vessel Code, Section V, limits the geometric unsharpness to one of four values depending on the part thickness as described below in Table 1.

Table 1 Allowed Geometric Unsharpness as a Function of Part Thickness.

Material Thickness (inches)	Maximum Geometric Unsharpness (inches)
Under 2	0.020
2 through 3	0.030
Over 3 through 4	0.040
Greater than 4	0.070

2.1.4 Area of Interest

The area of interest is the minimum area of radiographic coverage and is defined by the codes. The first three parameters discussed (Sections 2.1.1, 2.1.2 and 2.1.3) essentially define the image quality of the area of interest. The area-of-interest limits are indicated on the film by some form of marker. These are normally lead alphanumerics that have been placed directly on the object being radiographed. These markers are projected onto the film and locate the area of interest; they can also be used for the location of defects to be repaired and are referred to as section markers or stations.

2.2 Review and Evaluation of Standards for Digitization of Radiographs

Because film digitization is a relatively new technology, it is not surprising that there is little in the way of standards for the digitization of radiographs. The only current document we know is the ASME Section V, Article 2, Appendix III on digital image methods for radiography and radioscopy.[8] This recent document outlines in very broad terms the requirements for digitizing radiographs; specific details are generally absent except for the requirement to calibrate the system Modulation Transfer Function (MTF) using a line-pair test pattern and an optical density step wedge. Recommended or minimum performance values for the digital system are not specified. We also note that the ASME Code permits the reproduction of radiographs in selected situations by microfilm methods.[9] These two cited documents confirm that radiographs prepared for ASME inspection records may be reproduced.

Additional related standards are in preparation. For example, currently in ballot in ASTM Committee E-7 are documents on storage of digital data (see footnote 1 below) and a data field guide for digital radiological data (see footnote 2 below). The data field guide includes a listing of the parameters that should be given for a digital radiological file. Although the purpose of the guide is for the transfer of the digital file, the information will also be useful for a stored digitized radiographic file. There are several other existing standards related to the storage of radiological data.[10-12] Ref. 12 refers to other related ASTM and ANSI standards for film storage.

A variety of available standards could apply to the control and qualification of the digitization system. These standards are discussed below. Additional standards may be required to fully control the digitization process. Specific needs are also discussed.

ASTM E-746[4] provides a test method to determine image quality of radiographic film. The document describes a test object and a method for determining radiographic image quality on a finer scale than is permitted by conventional plaque-type[1] or wire[5] IQIs. This method can be used to take into account film characteristics, exposure and viewing conditions, and processing. The standard was designed specifically to evaluate the influence of variables that affect film quality. The document also describes a procedure for 200-kV X-ray inspection of a 19-mm (3/4 in.)-thick steel plate. A series of thin shims containing small holes of varying sizes is placed on the source side of the steel plate for the radiograph (shim thicknesses as small as 0.13 mm [0.005 in., 0.67% contrast] and hole diameters as small as 0.5mm [0.02 in.]). The visibility of small holes at low contrast presents a challenge for radiographic interpreters. We recommend that films of this type, designed to determine equivalent penetrameter sensitivity (EPS), as judged by experienced film interpreters, should be used to assess the performance of a digitized radiographic system and establish the equivalence of the digital image to that of film at an OD of 2.0. This would permit a comparison of the digitized result versus human interpreter evaluation on the basis of a consensus standard.

ASTM E-746 has limitations in terms of applicability for radiographs well beyond the 200-kV X-ray energy range; however, ASTM Committee E-7 is actively working on documents to extend the applicable energy range. One document in progress, for example, is titled "Standard for Determining the Relative Image Quality Response at High Energy."

There are other ASTM documents in progress that apply to radiographic interpretation capability. One of these is a document that addresses the determination of visual acuity for radiographic interpreters (see footnote below). This described procedure uses a series of crack-like images in which the crack (actually a slot) image is placed in different orientations and locations, the images are then presented at various contrast levels. This document

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[1] "Standard Guide for the Storage of the Media That Contains Analog or Digital Radioscopic Data," ASTM E-7 document in progress (1991).

[2] "Standard Guide for Data Fields for Computerized Transfer of Digital Radiological Test Data," ASTM E-7 document in progress (1991).

"Visual Acuity Testing for Radiographic Examiners in Nondestructive Testing," ASTM E-7 document in progress (1991).

is based on prior work at the National Institute of Standards and Technology.[6] The approach takes into account accepted ideas for visual perception.[7] This series of cracklike images at various contrast levels could serve as a method to qualify digitized radiographic methods.

Although we have cited a number of standards related to film digitization, it is our opinion that no existing standard specifies minimum requirements for a radiographic digitization system; this is the type of information under discussion in this NRC Task Group Report.

2.3 Minimum Radiographic Indication To Be Imaged

Specifications require the detection of a plaque-type penetrameter whose thickness is 2% of the material thickness and the detection of a 4T diameter hole in the plaque. For small thickness changes, one can assume that a 2% thickness change will give approximately a 2% contrast change. In this situation, a minimum density change of 0.02 OD must be detectable.

Past research indicates that a qualified film interpreter can detect density variations of at least half that value, or a density change of 0.01 OD.[13-14] Therefore, for faithful image reproduction in terms of equal performance for a film interpreter, the digitization system should be capable of displaying density variations that small.

Ideally, one would prefer a film digitization system that is capable of reproducing low-contrast indications of tight cracks. Radiographic detection of such cracks depends on many factors, including the angular orientation, length, and depth of the crack. In addition, radiographic detection can vary because of system parameters such as radiation source size, object-to-film distance, source-to-object distance, source energy, and film characteristics. Many system parameters relate to radiographic unsharpness,[13-14] a factor that includes geometry, film, screen, and movement parameters. At the energies needed for radiographic inspection of relatively heavy steel nuclear plant components, the unsharpness of double-emulsion film can be significant, i.e, on the order of 0.1 mm [15-16] The other major unsharpness factor in most situations is geometric unsharpness. The ASME Code places upper limits on geometric unsharpness varying from 0.5 to 1.8 mm. Total unsharpness increases as the square root of the sum of the squares of the contributors. Even if extreme measures are used to reduce geometric unsharpness, film unsharpness sets a lower limit for image detail size in a radiograph.

The impact of unsharpness on crack detection is that the film image of a narrow crack is spread in the emulsion and the contrast is reduced. Halmshaw [13] cites the example of a crack width of 0.025 mm radiographed under conditions of total unsharpness of 0.2 mm. Contrast for the crack image is reduced by a factor of eight from the theoretical maximum. The example numbers are reasonably realistic as applied to radiographic inspection of nuclear power plant components. Note also that the film representation of the crack is at least as broad as the total unsharpness. The anticipated film unsharpness of at least 100 µm provides a conservative estimate of the minimum image detail size, because additional factors, including geometric unsharpness and scattered radiation, would further broaden the image.

With these factors recognized, the spatial-resolution capability of some available film digitizers is adequate. The resolution is also somewhat confirmed by the recent work of Ciorau [15] which indicates that 300-kV X-ray examination of 48-mm (1.9 in.)-thick steel under ideal geometry conditions with a slow, fine-grain X-ray film shows a leveling characteristic for detection of cracks with widths of 100 µm or less. Ciorau's crack samples included widths down to 5 µm.

The results of the experimental work carried out by the Task Group are consistent with the results in the literature cited above. The Task Group's work consisted of radiographing two blocks butted together with gap width varying from zero to 300 µm. Radiography of these samples was performed with parameters that would produce considerably lower total unsharpness than might be expected in nuclear plant inspections. Microscopic examination of the radiographs revealed indications of these gaps as narrow as 30 µm. Digitization of these films at 70-µm digitizing spatial resolution produced a readable image of the gap in all areas, although with considerably greater width than was indicated on the films (and with lower contrast.) Thus the radiographic indication was not faithfully reproduced.

In addition to this experimental work, actual radiographs from an operating nuclear power plant were digitized at several facilities. These films represented a difficult case in that they were of a very high density and the indications were small, low-contrast, and barely visible to trained observers. The radiographs were digitized on seven different systems whose characteristics are tabulated below in Table 2.

The indications of interest in the films were visible in the digitized image on all systems with 12-bit digital fidelity and a DSR of less than 70 µm. They were not all visible on the 8-bit system or on the system with the DSR of 100 µm.

These and the experimental results support the accuracy of the calculated performance requirements.

Table 2. Results of Digitizing Radiographs with Different Systems

Facility	Detector	Light Source	DSR (μm)	Digital Fidelity (bits)	Results
1a*	CCD	White	70	12	Marginal
1b*	CCD	White	70	12	Marginal
2a	CCD	White	70	12	Unacceptable
2b	CCD	White	[illegible]5	12	Good
3	CCD	White	[illegible]5	12	Good
4	PMT	Coherent	100	12	Unacceptable
5	Video	White	Variable	8	Unacceptable

*These two systems use an older technology chip [illegible]s a blooming problem and the systems have a lower intensity light source than current systems.

3 PERFORMANCE REQUIREMENTS

Four basic parameters determine system performance: (1) digitizing spatial resolution (DSR), i.e., pixel size or spacing; (2) dynamic range; (3) digital fidelity (e.g., 12 bits); and (4) minimum detectable film density change. DSR is the determining factor in the spatial-resolution limits of the system. Dynamic range is the span of film density that can be scanned and detected without significant noise or detector saturation. Digital fidelity is the number of bits obtained from the analog data. The minimum detectable film density change is dependent upon digital fidelity and noise level. All of these performance factors may be characterized as a single function known as the modulation transfer function (MTF). The MTF can be obtained from the image of a standard that has, for example a periodic rectangular line pattern of varying spatial frequency with optical densities of at least 4.0 in the dark bars and less than or equal to 0.2 OD in the light bars. The MTF should ideally be used as a measure of system performance.

From a different standpoint, system performance depends on the size film that can be digitized, the time required to digitize a radiograph, and the maximum image size that can be processed and stored. These variables affect primarily the throughput and efficiency of the process and will, therefore, not be addressed in this report.

3.1 Specifications for a Film Digitization System

The requirements for a system to digitally capture and store radiographs are presented in Table 3. The specifications are presented for a 50-μm digitizing spatial resolution. The size of the image matrix is for a 14 x 17 in. film. Smaller matrices could be used, although in those cases the film would be reproduced in two or more sections.

3.2 Justification of Specifications

Contrast Sensitivity. Arguments for selection of a value of 0.01 for optical densities up to 3.0 were provided in earlier discussion. (See Minimum Radiographic Indication to Be Imaged.) At optical densities above 3.0, the intensity of transmitted light becomes very low and reduces the detectable change in density. Experience suggests that a density change of 0.03 OD is detectable and is appropriate for high-density areas.

Digitizing Spatial Resolution (DSR). To faithfully reproduce 100-μm features, a DSR providing at least 2 pixels across that width is needed, thus justifying the selection of 50-μm spatial resolution. In this document, faithful reproduction implies that the image-detail visibility in the digital image is equivalent to that on the film.

Dynamic Range. ASME code requirements permit films to have background densities in the range of 1.2 to 4.0, as discussed above. Discontinuity indications may extend that range (either lighter or darker). For example, a tungsten inclusion may produce a film density close to base plus fog (≈0.15), while a pore or crack will produce a darker indication than the background density.

System-Specific Signal-to-Noise Ratio (SNR). The SNR has a strong impact on the imaging of low-contrast details. The values specified, in conjunction with the other parameters, provide a reasonable assurance that a 100-μm feature at 0.01 (or 0.03) OD will be detected with at least a 2-to-1 SNR.

Table 3. Specifications for a radiograph digitizing system capable of reproducing 100 μm features.

Parameter	Specification
Contrast sensitivity	< =0.01 OD(< 3 OD) < =0.03 OD (3-4.5 OD)
Digitizing spatial resolution	< =50 μm
Dynamic range	0.15-3.5 OD to 1.0-4.5 OD
System-specific signal-to-noise ratio	> =2000:1 at 2.0 OD > =300:1 at 3.5 OD
Modulation transfer function	> = 0.33 for spatial frequencies up to 5 lp/mm
Digitization range	> =12 bits/pixel
Monitor resolution	> =1024 x 1280, noninterlaced > = 70 Hz refresh rate
Data storage	Write once/read many or equivalent
Enhancement functions necessary for viewing on CRT Windowing	Histogram equalization Contrast stretching
	Zoom
Data compression	Lossless

Modulation Transfer Function (MTF). Detection of a 100-μm feature requires a spatial resolution of 5-lp/mm. A contrast sensitivity of 0.01 over a dynamic range of 3.5 OD (a practical limitation within a single scan) implies a contrast sensitivity of 12 gray-scale levels (GSL) in a 12-bit system.

$$0.01/3.5 \times 4096 = 12 \text{ GSL}$$

With a SNR ratio of 2000:1 at 2.0 OD, one would expect a maximum noise signal of 2 GSL. To ensure detection, the 0.01 feature should then have at least a 4-GSL variation from background. We can therefore tolerate a modulation of the detail contrast to 4/12 (33%) of the theoretical value. Hence the 5-lp/mm detail must have at least a 33% modulation.

Digitization Range. Film provides a dynamic range of more than the 12 bits/pixel available for digitization. While the human eye cannot differentiate the resulting 4096 levels of gray, an experienced professional can distinguish between film digitized at 10 bits/pixel and that digitized at 12 bits/pixel (an 8-bit system is clearly inadequate).[17] A 12-bit/pixel system, including storage (frame buffer), digital-to-analog converter, video amplifier, and CRT is preferred for digitizing radiographs.

Monitor Resolution. Monitor resolutions of at least 1000 lines, used at normal operating distances, have been shown to reduce eye fatigue due to the inability to resolve the scan lines. High resolutions are needed to present the large amount of data collected from the radiographs in a reasonable amount of time.

Data Storage. Write once/read many (WORM) data storage systems provide the maximum degree of data security because data cannot be changed or erased once written to the storage media. Current optical-disk storage media provide high-volume storage capacity for the large files generated by the required DSR.

Enhancement Functions Recommended. The listed functions are considered the minimum required to fully interpret the digital radiographic image. High- and low-frequency filtering as well as inverse video are other relevant options. Refer to Appendix A for a full discussion of these and other enhancement functions.

Data Compression. Fully reversible (lossless) data compression is required to ensure that no data is lost in the compression process.

3.3 Standards

Although several standards related to film digitization have been discussed, no known existing standard specifies minimum capability for a radiographic digitization system.

Initial system qualification and periodic system checks must be performed to ensure proper use of film digitization systems. To date, no known standards cover initial system qualification and periodic system checks. The following tests are recommended:

1. Verification that the system meets the identified performance requirements.

2. Use of a set of four ASTM E-746[4] films that have been read by three film interpreters to establish equivalent penetrameter sensitivity (EPS) and that have shown less than 100% detection of holes. The scanned films should show at least as many holes as were read by the average of the three interpreters.

3. A standard test pattern film will be used to qualify the performance of the system in daily use. The standard test pattern film should verify the dynamic range, spatial resolution in two directions, and contrast sensitivity of the digitizer. Measurement parameters should be made at the corners of the digitization field and in the center. Dynamic range will be measured with a stepped optical-density scale covering the range from 1.0 to 4.5 OD. Spatial resolution will be checked using a 5-lp/mm resolution target in both the vertical and horizontal directions, and contrast sensitivity will be measured with a pair of test patterns consisting of a 1-cm square with a density slightly lower than the surrounding 4-cm square. One such pattern should include a 1.95-OD square in a 2.0-OD field. The other pattern shall include a 3.40 optical density square in a 3.5 OD field. The number of GSL variations must be measured between the background and the central square. For the 2.0-OD pattern, the GSL variation must be divided by 5 to arrive at an equivalent change for an 0.01-OD step. The resulting value must be above the system noise level. For the higher-density pattern, the measured GSL change must be divided by 3 to relate to a 0.03-OD change, and this value also must be above the system noise level. The contrast sensitivity patterns may have a density that varies by up to 0.15 OD from those specified as long as the contrast differentials of 0.05 and 0.10 are maintained.

4. Data compression schemes must be verified as lossless. A typical approach would be to digitize one of the standard test films, then compress and decompress the file. The decompressed file is then subtracted from the original file. If truly lossless compression was used, the resulting image should be completely black (all zeros).

One or more new standards should be developed to control the initial equipment qualification and daily performance checks identified above for the digitization equipment.

4 EXISTING TECHNOLOGY

In this section, the technology currently available for digitizing radiographs will be discussed. Included is a description of the hardware, specifications of various systems, and image-enhancement options. This information relates to the existing technology to perform the needed digitization, storage and handling of the digitized records.

4.1 Background

Radiographic film represents an extremely effective information system for presentation of the density/thickness/composition contrast available from a specimen. Film radiographs record more than four decades of radiation absorption information in a true image format that is readily interpreted and understood. The image may be viewed with inexpensive light sources, provides extremely high spatial accuracy, and may be archived for long periods of time. Film is the most cost-effective and high-quality system for the acquisition, display, and archiving of radiographic information available at this time.

However, film also lacks certain desirable characteristics. Some of these characteristics may be made available through digital electronic imaging, including extended exposure latitude, image communication, improved archiving (smaller storage space, longer storage time with less loss of image quality, and easier image retrieval) and image enhancement.

The improvements offered by digital electronic imaging are just now becoming physically and economically possible. These improvements must, however, be obtained without loss of the image information already in the film on hand. This summary was made to examine the state of the art of digitization of existing radiographic films to improve the storage life and preservation of the information in those films.

4.2 Equipment

The state-of-the-art equipment available today seems quite capable of providing digital copies of existing radiographs that are essentially identical to the originals. In fact, most digitization techniques provide some slight improvement in the readability of the digital image over the original. For example, the digitization process provides an averaging of the density variations in small areas of the film. This improves the SNR of the image as interpreted by the eye.

The two major digitization approaches are (1) use of a high-resolution, multielement charge-coupled device (CCD) linear array to read white light transmitted through the radiograph from a uniform strip light source and (2) use of a linear array of photodiodes or a photomultiplier tube to read light transmitted through the radiograph from a laser beam scanned across the film. Parameters from these systems are listed in Table 4.

Digitizer. The digitizer system converts processed films to a data format that can be archived, enhanced, communicated, and evaluated through a computer-based imaging system. The films are digitized into a pixel array, the size of which is dependent upon the spatial resolution selected and the film size. Common resolution values are from about 400 down to 35 µm. Each pixel-array value is represented as 12-bit or greater values of the optical density at that point in the film. Optical density ranges of 0 to 3.5 up to 1.5 to 5.0 may be digitized.

Table 4 . Digitization Parameters and Existing Technology

Parameter	Current Capabilities
Digitizing Technique	
Illumination source	Moving laser spot or white-light strip.
Detector	Photodiodes, photomultiplier tubes or charged-coupled device arrays.
Digitizing spatial resolution	35 to > 400 µm
Density range	0.0-3.5 to 1.5-5.0 OD
Signal-to-noise ratio	4000:1 to 9700:1 at 2.0 OD 1000:1 to 2900:1 at 3.0 OD 700:1 at 3.5 OD 540:1 at 4.0 OD
Modulation transfer function	5-lp/mm at 0.40 and better
Digital fidelity	12-16 bits
Data storage	Write once/read many
Film sizes	Up to 14 x 17 in.

Digitizing techniques typically use either a uniform line or area of illumination or a scanning spot of light from a laser. Uniformity of the line or area illumination is an inherent problem in the scanning technique, in which a spot of light is scanned across the film by a moving mirror. The moving mirror can be a rotating polygon or on a galvanometer. Wear in the moving system can cause loss of system resolution and accuracy. A more serious problem is the changing angle that the spot of light makes with the film surface. This is particularly critical in double emulsion films (up to 180 -µm thick) and with the use of a 50-µm or smaller spot, where, for example, at an incident angle of about 25° from normal, a full pixel of displacement occurs in the digitized image of the two emulsions. Light scattering also becomes a problem with either spot scanning or illumination because the thick film scatters light from the intended pixel to other pixel positions. Some systems provide corrections to minimize these problems.

There is a significant tradeoff between spatial resolution (spot) versus storage space for the data and time to digitize the film. If the spot is relatively large compared to the information resident in the film, information from the film will be lost in the digitizing process. However, as the spot size decreases, considerably more data storage space is required and the process takes longer. For example, if the spot is reduced from 200 to 100 µm, four times the space is required for storage and display of the image, and the time required to digitize the film four times longer.

This is illustrated in Table 5 for a 14 X 17 in. film using a 12-bit digitizer.

Table 5. Required Storage Space as a Function of Pixel Size

Pixel Size (μm)	No. of Pixels	Storage Space (Mbytes)
200	1778 x 2159	7.677
100	3556 x 4318	30.71
50	7112 x 8636	122.8

Obviously, extremely small spot sizes can quickly exceed the storage space capacity of even optical disk media when many images from large films are digitized.

Large detector arrays made from photomultiplier tubes, photodiodes, and CCDs have been used. Each detector type has its own advantages and disadvantages in terms of stability, cost, and auxiliary requirements. Photomultiplier tubes require extremely stable power supplies to provide stable outputs. Photomultiplier tube output can vary as the 6th to 10th power of the applied voltage change and can transfer ripple from the power supply to the signal.

Photodiodes are available in arrays (originally for Fax machines) that could be appropriate for the digitizing system. The length of these arrays is currently limited to 8.5 in. Production of 14-in. arrays should begin this year. The photodiode arrays have excellent linearity of over four decades of incident luminous flux with good quantum efficiency. However, the available systems are limited to 85 μm sampling over a maximum length of 8.5 in.

CCD linear arrays are now available with 6000 elements of about 10 μm each. They lack the desired dynamic range and sensitivity and require temperature regulation or thermoelectric cooling to reduce dark current to acceptable levels. With electronic processing, the dynamic range of the antiblooming CCD sensors has been made acceptable.

Data from the CCD arrays can be digitized rapidly so that films can be read in seconds. With the data leaving the CCD in two streams at 5 MHz, scan rates of 800 lines/s can be obtained.

Data Processing. Data processing in digitization includes analog signal conditioning, analog-to-digital (A/D) conversion, log conversion, and data correction techniques. These processes are well known and established for each of the detector systems described above. Newer detector systems require corrections for dark current and for sensitivity variations in the individual elements. Such electronics are often sold as an integral package with the detectors.

Other signal handling is rather straightforward. Each system will have its own corrections, transformations, and amplification requirements which are readily available and match standard technology.

Mechanical Considerations. Other than wear in rapidly moving mirror systems, the major mechanical considerations for digitizing systems will most likely be the automated film handling systems and the variable-spot-size selection arrangements. Film handling is an important consideration in the systems that must have high throughput for economical handling of the many films that must be digitized at a single nuclear facility. Handling is critical in terms of film registration, alignment, and identification, and possibly in recognition of film sizes. Also recommended are features such as audio signals for jams and other malfunctions, indications of empty input or full output containers, and automatic handling of different film sizes and thicknesses.

Experimental Evaluation. Experiments have been conducted with private and commercial film digitizing systems to determine the acceptability for reproduction of radiographs from nuclear power plants. These experiments include digitization of radiographs with a) difficult-to-image indications, b) images from two blocks butted together with varying gap widths (0 to 300 μm), c) wide optical-density ranges for the varying gap width radiographs and d) image quality indicators (IQI). Results of these experiments have convinced the task group that the present state-of-the-art commercial systems can satisfactorily digitize code-acceptable radiographs for archiving and screen (CRT) display.

4.3 Image Processing

Radiographic interpretation is the skill of applying visual acuity to extract needed information from a radiographic image. The detectability threshold, however, varies from interpreter to interpreter and is dependent on the interpreter's training, experience, and visual perception ability. The result is a subjective interpretation of radiographic images. It is therefore appropriate to use image processing techniques on digitized radiographs as an aid to film interpretation.

The concept of a "processed image" should not be new to the experienced film interpreter. One only has to understand how an image is formed on a film to realize that a radiograph is one form of a "processed image." Factors such as exposure parameters, processing conditions, and viewing conditions all significantly affect the image enhancement of film systems. Furthermore, one should not hesitate to apply digital image processing techniques as long as the original digitized image data are preserved and the interpreter has a basic understanding of image processing, which is required for the interpretation of processed images.

Conventional digital image processing is concerned with the manipulation and analysis of digital images. Its major subareas include enhancement, restoration, analysis, and data compression. In addition, simple image manipulations such as rotation, flip, and zoom, are often necessary.

4.3.1 Image Manipulation

Proper positioning of digitized images often require the rotation of the image by 90° or 180.° It may also be desirable to flip the image because the film has been digitized up-side down. Zoom provides magnified viewing of areas of interest within a digitized image.

4.3.2 Image Enhancement

The main goal in image enhancement is to accentuate certain and often subtle image features for subsequent analysis or display. The enhancement process itself does not increase the inherent information content in the data, but does increase the visibility of the chosen features so that they can be detected more readily. The enhancement functions listed in Table 3 are considered the minimum required to fully interpret the digital radiographic image. Image enhancement techniques are discussed in Appendix A.

4.3.3 Image Restoration

Image restoration refers to improving the fidelity of an image by compensating for image noise and blur, assuming certain degradation models and/or the use of statistical or deterministic knowledge of signal and noise. This includes deblurring of images degraded by the limitations of a sensor or its environment, noise filtering, and correction of geometric distortion or nonlinearities due to sensors. The effectiveness of image restoration filters depends on the extent and the accuracy of the knowledge of the degradation process, as well as on the filter design criterion.

Image restoration differs from image enhancement in that the latter is concerned more with accentuation or extraction of image features than with restoration of degradations. Image restoration problems can be quantified precisely, whereas enhancement criteria are difficult to represent mathematically. Consequently, restoration techniques often depend only on the class or ensemble properties of a data set, whereas image enhancement techniques are much more image dependent.

There are many types of degradation in imaging systems. One type, called point degradation, affects only the gray levels of the individual pixels and does not involve spatial blur. Other types that do involve blur are called spatial degradations.

A commonly used method for image restoration involves the use of a Wiener filter. This filter gives the best linear mean square estimate of the object. The method can be implemented in frequency domain via fast unitary transforms, in spatial domain by two-dimensional recursive techniques similar to Kalman filtering, or by Finite Impulse Response (FIR) nonrecursive filters.

Several other image restoration methods such as least squares, constrained least squares, and spline interpolation methods can be shown to belong to the class of Wiener filtering algorithms. Other methods such as maximum likelihood, maximum entropy, and maximum a posteriori are nonlinear techniques that require iterative solutions.[18]

4.3.4 Image Analysis

Image analysis is concerned with making quantitative measurements of an image to produce a description of the image. In the simplest form, this task could be the reading of a label (bar code) such as used on a grocery item, sorting parts on an assembly line, or measuring the sizes and orientations of blood cells in a medical image. More advanced systems measure quantitative information and use it to make a sophisticated decision. In this sense, image analysis is quite different from image enhancement and image restoration, where the output is another image. Image analysis basically involves feature extraction image segmentation, and classification techniques.

Feature extraction is the identification of features that are deemed useful to the interpreter. Examples include spatial feature extraction, transform feature extraction, edge and boundary detection, region representation, moment representation, and texture analysis. Extraction of nonimage data, such as a cross section, can provide important statistical information about the feature and/or image.

Image segmentation refers to the decomposition of a scene into its components. It is a key step in image analysis. For example, a document reader would first segment the various characters before identifying them. Image segmentation techniques include amplitude thresholding, component labeling, boundary labeling, region-based and cluster labeling, template matching, and texture segmentation.

A major task after feature extraction and/or image segmentation is classification of the image. Many classification techniques can be found in pattern-recognition literature. A review of a few techniques will establish their relevance in image analysis. It should also be mentioned that classification and segmentation have closely related objectives; classification can lead to segmentation and vice-versa.

There are two basic approaches to classification (supervised and nonsupervised), depending on whether or not a set of prototypes is available. Supervised learning, also called supervised classification, can be distribution-free or statistical. Distribution-free methods do not require knowledge of a priori probability distribution functions and are based on reasoning and heuristics. Statistical techniques are based on probability distribution models, which may be parametric (i.e., Gaussian) or nonparametric. In nonsupervised learning, we attempt to identify clusters or natural groupings whose local density is high compared to the density of the feature points in the surrounding region. Clustering techniques are useful for image segmentation and for classification of raw data to establish classes and prototypes. Clustering is also a useful vector-quantization technique for image compression.

4.3.5 Data Compression

Despite the advantages of digital image processing, one potential problem with digital images is the large number of bits required to store them. For example, a 14 x 17 in. radiograph scanned at 50 μm and 12-bit resolution results in a digitized image that contains 7,112 x 8,636 pixels, which translates into 122.8 Mbytes of data. Fortunately, digital images in their canonical representation generally contain significant redundancy. Image compression, which is the art/science of efficient coding of picture data, aims at taking advantage of this redundancy to reduce the number of bits required to store an image. This can result in significant savings in the memory needed for image storage or in the channel capacity required for image transmission. The efficiency of data compression, known as the compression ratio, is measured as the number of bits in the original image divided by the number of bits in the compressed image. In general, data compression can be categorized into lossless or lossy data compression techniques.

In lossless compression, known as bit preserving or reversible compression, the reconstructed pixel values (compressed/decompressed) are *numerically identical* to the original image on a pixel-by-pixel basis. A simple test consists of subtracting the original image from the decompressed new image and verifying that a matrix of zeros is obtained. Obviously, lossless compression is desirable because there is no loss of information. However, only a modest savings is accomplished using lossless compression. Typical compression ratios, which are dependent on the texture of the original picture, range from 2:1 to 4:1. Examples of lossless techniques include bitplane encoding, run-length encoding, predictive coding and adaptive arithmetic coding. Compression efficiency varies somewhat for the different techniques, but each offers certain features and aims at satisfying requirements that might exist in a particular environment.

In lossy compression, as the name implies, some discrepancy exists between the original and reconstructed pixel values. Degradations are allowed in the reconstructed image in exchange for an increased compression ratio relative to lossless techniques. These degradations may not be visually apparent, and greater compression ratios can be achieved by allowing more degradation. The task group considers lossy compression techniques to be unacceptable.

4.4 Performance Demonstration

As a result of its experiments and evaluations, the task group feels there is a need for personnel with both radiographic interpretation skills and digitizing equipment operation skills in order to produce quality archived radiographic images. These personnel should be skilled in the proper selection and use of image processing techniques and in interpreting and analyzing of the digitized radiographic images. Furthermore, equipment meeting minimum specifications and capable procedures need to be used by qualified personnel in order to develop faithful digital images of flaw indications of interest on the radiographic films. Therefore, a performance demonstration test for qualification of the digitization process which includes the personnel, procedures and equipment is required. The "digitization process" as used in this report is meant to encompass all those actions, procedures, equipment and personnel that are used to digitize radiographic film leading to the faithful reproduction of images that can be properly interpreted with respect to image quality and flaw detection, classification and sizing. Successfully passing performance demonstration tests that establish, for the flaws of interest, high probability of detection, correct classification of the flaw types and accurate flaw sizing adds confidence that faithful digital reproduction of radiographic film images has been achieved.

The specifications defined in previous sections for digitization of radiographs should assure the faithful digital reproduction of films containing flaw indications of interest. However, performance demonstration results from qualification of various digitization processes may indicate that some adjustment in the specifications for one or more parameters may be desirable or acceptable. Appendix B to this report presents information, criteria and requirements for performance demonstration testing for qualification of radiographic film digitization processes.

5 IMPLEMENTATION

The task group, through discussions and evaluations of radiographic film digitization, has determined that the technology for faithful reproduction of radiographic images is acceptable if the recommendations and specifications in this report are implemented. The task group further recommends that existing radiographs be digitized as soon as possible to prevent further loss of information due to aging of the current records. Digitization may also be considered desirable by the industry to support requests for license renewal.

The NRC position for digitizing radiographic images should be provided in a generic letter. Guidance for NRC inspectors can be provided through an update of Inspection Procedure 57090 of the Inspection & Enforcement Manual. The performance requirements are described in this report. In addition, several comments should be made about the implementation of the technology; these comments are primarily of the type that will assist in the transition from the radiographic film to the digitized images as the permanent plant record. The comments, together with discussion about their importance, are listed below.

Comment 1: Only "Code Acceptable" radiographs should be digitized and stored as the official plant record. Digitization of radiographic film is not intended to improve for acceptance an unacceptable radiograph.

Discussion: Existing radiographic records are considered to be Code Acceptable and ready for digitized storage. However, a statistical sample of the radiographs to be digitized should be reviewed to ensure acceptable quality. Radiographs whose quality has degraded because of aging are acceptable for digitization, and in fact, should be digitized to prevent further loss of information and to take advantage of image enhancement techniques. Radiographs found to have been of unacceptable quality since inception should be handled as a separate issue.

For new work (repair, modification and new construction), radiographs should be reviewed for code acceptance of the radiograph and of the component before the radiograph is digitized for storage.

Comment 2: For operating plants, flaws discovered during the review of the digitized radiographic images should be evaluated according to ASME Section XI rules.

Comment 3: Digitization and evaluation of digitized radiographs should be conducted by qualified personnel who have passed performance demonstration tests (personnel, procedures, equipment) as discussed in Appendix B. When a flaw is discovered during the review of a digitized radiograph, an independent evaluation should be conducted by a second qualified reviewer, and if consensus cannot be reached, the most conservative evaluation should be used in determining the acceptance of the component. The proper use of image processing (enhancement) functions can be of value in reaching such a consensus.

Comment 4: After proper digitization, storage, and acceptance of radiographic images, the radiographs may be discarded.

Discussion: The digitized images become the official record after they have been accepted through the Quality Assurance (QA) program. The QA program should include considerations about the proper calibration and operational verification of the equipment (see Sec. 3.3). Operational verification of the digitizing equipment, by an approved standard test pattern radiograph and companion diagnostic software, should be conducted at the beginning and end of each shift and periodically as required. Each verification test should be archived with the digitized radiographic images as verification that the process worked correctly. (At a minimum, each optical disk should contain at least one operational verification.)

The QA program should consider the handling of special cases, such as when multiple film viewing was required for the acceptance of the component. The equipment should be demonstrated as capable of either scanning the multiple films together as the record or scanning the individual films separately and then overlaying the digitized images through software to simulate the original composite viewing.

Comment 5: The ASME Code Section V, Article 2, Mandatory Appendix III—Digital Image Acquisition, Display and Storage for Radiography and Radioscopy, provides an acceptable framework for the digitization of radiographs.

Discussion: This appendix is only a qualitative document and must be supplemented with the quantitative specifications and performance demonstrations presented in this report. Proper implementation of the calibration and performance specifications described in this Task Group report will ensure faithful reproduction of radiographic images. For this reason, we believe that the viewing considerations requirements of Section III-234 of the appendix can be met by statistical sampling.

With respect to Section III-222 of the appendix, we believe that information concerning artifacts can be a part of the reader information package, as discussed in the next comment below.

Comment 6: Everything that is contained in the record package for the final acceptance radiograph should be digitized.

Discussion: The reader information package (i.e., radiographic technique sheets, reader sheets, etc.) for each radiograph should be digitized along with the radiograph, or digitized in a separate WORM file that is cross-referenced to the radiograph file. The support information provided by the reader information package (including artifacts) should be stored in a file system that allows searching the data base by other than weld or radiograph identification, (e.g., material, pipe size, date, radiographic interpreter, etc.)

Each piece of radiographic film within the record package should be digitized in its entirety.

Comment 7: USNRC Generic Letter 88-18, Plant Record Storage on Optical Disks, dated October 20, 1988, (included as Appendix C) provides an acceptable framework for the storage of digitized radiographic images.

Discussion: This letter provides guidelines for the replacement of paper records with optical disks, but the digitization of radiographic images is much more complex than the scanning of paper records and therefore additional guidelines, such as those discussed earlier in this report, are required for faithful reproduction. The rules provided by the Generic Letter should not be limited to optical disk technology as long as the WORM principle is adhered to.

To expand on the final bullet of the Generic Letter, which discusses the replacement of the imaging system with an incompatible new system, care must be taken to preclude loss of records if the existing imaging system fails before the data are transferred to a new system. Adequate documentation of the system used to store the digitized data, including details of the file format, will ensure that the data can be retrieved in the future.

Comment 8: Digital image processing (enhancement) functions are necessary for the proper display of digital images. The required enhancement functions are listed in Table 3 and are more fully discussed in Appendix A of this report.

Discussion: The concept of a "processed image" should not be new to the experienced film interpreter. One only has to understand how an image is formed on a film to realize that a radiograph is one form of a "processed image." Furthermore, one should not hesitate to try additional image processing techniques as long as the original digitized image data are preserved and the interpreter has a basic understanding of image processing and is qualified, as recommended in this report, to interpret processed images. The proper use of image enhancement can be of value in resolving disagreements regarding the nature (type, size) of flaw indications and the acceptability of components.

Comment 9: Data compression for economizing data storage requirements is useful and acceptable when the data compression is of the lossless type. A simple test for determining if the data compression is lossless was discussed earlier in Section 4.3.5 of this report.

6 CONCLUSIONS AND RECOMMENDATIONS

We have defined the specifications for the digitization of radiographs that will satisfy the needs of the nuclear industry. A 12-bit system with a modulation transfer function (MTF) of 0.33 at a spatial frequency of 5-lp/mm and a spatial resolution of 50 µm will be required to adequately capture and store the image of a 100-µm feature with a 0.01 contrast, the smallest feature likely to occur on a radiographic film exposed under typical industrial conditions. Film densities in the range of 1.0 to 4.5 optical density (OD) must be accommodated by the system. A write once/read many (WORM) storage system will also be required.

We recommend that films, designed to determine equivalent penetrameter sensitivity (EPS) as judged by experienced film interpreters, be used to assess the performance of a digitized radiographic system and establish the equivalence of the digital image to that of film at 2.0 OD. This would permit a comparison of the digitized result with the human interpreter evaluation on the basis of a consensus standard (ASTM E-746). Although we have cited a number of standards related to the film digitization issue in this report, it is our opinion that no existing standard specifies minimum capability for a radiographic digitization system. To ensure system performance, we recommend that standards be developed to govern the qualification and operation of the system. Image processing must be carried out by qualified personnel.

The state-of-the-art equipment available in today's market seems capable of providing digital copies of existing radiographs that are essentially identical to the originals. In fact, most digitization techniques provide some slight improvement in the readability of the digital image over the original through enhancement techniques, although the enhancement process itself does not increase the inherent information content.

Enhancement does, however, increase the visibility of the chosen features so that they can be detected more readily.

As a result of its experiments and evaluations, the task group concludes that personnel skilled in both radiographic interpretation and digitizing equipment operation are needed in order to produce high-quality archived radiographic images. These personnel should be skilled in the processing, interpreting and analyzing of the digitized radiographic images. Image processing must not lead to the loss of data acquired in the initial digitization. The task group, therefore, recommends that a performance demonstration test be required for qualification of the digitization process which includes the combination of personnel, procedures and equipment.

Only "Code Acceptable" radiographs should be digitized and stored as the official plant record. Digitization of radiographic film is not intended to improve for acceptance an unacceptable radiograph.

Generic Letter 88-18, Plant Record Storage on Optical Disks, dated October 20, 1988, provides an acceptable framework for the storage of digitized radiographic images.

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APPENDIX A: IMAGE ENHANCEMENT

Introduction

The main goal in image enhancement is accentuation of certain often subtle image features for subsequent analysis or display. The enhancement process itself does not increase the inherent information content in the data. Enhancement does increase the visibility of the chosen features so that they can be detected easily. Image processing includes contrast and edge enhancement, histogram modification, sharpening, magnification, and noise filtering. The greatest difficulty in image enhancement is quantifying the criteria for enhancement. The algorithms used for image enhancement are often interactive and application-dependent. Quite often, one must experiment with the algorithms before obtaining satisfactory results. Point, spatial, and transform operations, along with pseudocoloring, are all common image enhancement techniques.

Point operations involve the mapping of individual pixel values onto another value according to some predetermined transformation. These operations include contrast stretching, clipping, and histogram modeling. The goal of contrast stretching is to improve the contrast of the image by amplitude-rescaling of each pixel. An almost infinite number of schemes exist; example schemes are sawtooth contrast scaling, sawtooth reversal, and level-slicing. A special case of contrast stretching is called clipping. In this scheme, certain ranges of pixel values are set to zero and the resultant is rescaled. This is useful for noise reduction when an input signal is known to lie within a certain range. The histogram of an image represents the relative frequency of occurrence of the various gray levels in the image. Histogram modeling, a powerful tool for image enhancement, modifies an image histogram so that it has a desired shape. This is useful in stretching the low-contrast levels of images with narrow histograms. Examples include histogram equalization, histogram modification, and adaptive histogram equalization. A particularly useful transformation is from raw digitizer output to some physical attribute such as the density or thickness of the object being evaluated.

Spatial operations are based on local-neighborhood pixels. Often, the image is convolved with a finite-impulse-response filter called a spatial mask. Examples of spatial masks are low-pass filters, median filters, and high-pass filters. Low-pass filters are useful for noise smoothing and interpolation, while high pass filters are useful in extracting edges and in sharpening images. Band-pass filters are effective in enhancing edges and other high-pass image characteristics in the presence of noise.

In transform operation enhancement, the image is first transformed with a transform domain operation. If the transformation is linear, this simply becomes a pixel-by-pixel multiplication. Examples of popular image transforms are the discrete Fourier transform (DFT), discrete cosine transform (DCT), Walsh-Hadamard transform (WHT), and Karhunen-Loeve transform (KLT). The transform operation provides a spectral decomposition of an image into coefficients that tend to isolate certain features of the image. For example, the first DC spectral component is proportional to the average image brightness, and the higher spatial-frequency components are measures of edge content. The enhancement techniques are performed in this domain and then a reversed transformation is done to produce the enhanced image.

Enhancement of images through the use of pseudocolor can be a powerful technique, but must be done with care to avoid interpretation errors. For example, an image with smoothly varying intensity values will appear to have smoothly varying gray tones when viewed as a monochrome image. If the intensity variations are small, the image will appear uniform. If the same image is displayed in pseudocolor, intensity variations can be shown very graphically. However, care is required to avoid interpreting "abrupt" color changes as abrupt intensity changes. This problem is alleviated by displaying a color scale with the image, and by the experience of the interpreter. Overall, pseudocolor provides visually striking and useful images, enabling interpretation of difficult areas when interpreted carefully.

In image reconstruction, the similarity of the picture to the undisturbed idealized form is the measure of success. In image enhancement, subjective problem-dependent criteria are used to design image-enhancement techniques. More-detailed discussion is presented below.

Compensation of Nonlinear Characteristics

Image signals can be sensed or displayed with nonlinear characteristics (e.g., contrast). Corrections are made by pixel-to-pixel mapping. The exponential decay of X-rays in radiography, for example, can be largely linearized by the logarithmic presentation of the recorded beam intensity values. Nonlinearity can be established in many cases by the image of a linear gray-scale wedge.

Intensity Scaling

After determination of the maximum and minimum intensity range (and associated gray-scale values) of the object of interest, the values within the bounds can be spread over the entire gray-scale range to provide more gray-scale values of the object. Even this simple pixel operator often produces images in which defects are more readily discerned.

Histogram Equalization

Because intensity scaling can be relatively time consuming, an automated scheme is often preferred. Frequently, the intensity values of the image must be distributed as evenly as possible over the entire available gray scale. The result for dark images is a dramatic improvement in contrast and the ability to observe details as low-intensity pixels are shifted to higher values.

Compensation of Illumination and Sensor Inhomogeneities

Both intensity scaling and histogram equalization are independent of spatial coordinates. Scaling could, in principle, be dependent on coordinates. For example, a shading correction might be required because of inhomogeneous exposure of the radiograph. This correction can be made by an image-acquisition system with a test pattern of constant reflection or transmission. The resulting image is the reference image used to compensate for the distortion.

Local operators map into the output image the intensity values within a local image window, according to a function to be defined. Several possibilities are discussed below.

Linear Smoothing Operators

To reduce finely structured erroneous intensity fluctuations, linear smoothing is frequently performed on the distorted image signals. The operation is typically on a window of 3 x 3 pixels, 9 x 9 pixels, or even larger. A simple example, resulting in smoothing of an image and reduction of fine detail, is the averaging of the values in a window and then reassigning the center pixel that value, or giving the average value to all pixels in the window. The effect is a low-pass filter that can reduce noise.

Median Filter

Improvements in noisy signals by space-invariant low-pass filter operations are compromises between suppression of noise and retention of fine detail. Use of a median filter generally eliminates [illegible] disadvantage. With this filter, the n (odd) elements [illegible] a local operator window are sorted by value. The resulting output image element is then the (n + 1)/2 highest value of the series. Bright/dark transitions (such as edges) are retained; they do not lose sharpness as in the case of smoothing. Structures that enter the window and whose extent is less than (n-1)/2 points (lines, corners, etc.) are eliminated.

Signal-Dependent Smoothing Operators

The disadvantage of suppressing high-frequency image structures (loss of image details, blurring of abrupt light/dark edges) and of aliasing of nonlinear filters in image regions with low-frequency-intensity fluctuations can be avoided somewhat by signal-dependent space-invariant smoothing operators. It is assumed that the image can be subdivided into regions with low fluctuation in gray values and regions with sharp transitions in gray values. Regions with sharp light-to-dark transitions can be identified by a gradient operator and a subsequent threshold operation. The improvements obtained with signal-dependent smoothing operators are much greater than those achieved with space-invariant filters.

Image-Sharpening Operators

Fine-image structures are exaggerated with image-sharpening operators. Also, blurred object edges are deblurred, but signal noise is generally amplified in the image. With image-sharpening operators, low-spatial-frequency components are attenuated more strongly than are high-spatial-frequency components. An appropriate low-pass response can generally be chosen intuitively under visual control. Either linear or nonlinear low-pass filters can be used.

Linear Low-Pass Filters

Low-pass filtering suppresses noise in the image. Implementation in the spatial-frequency domain can be accomplished by multiplying the transfer functions by the image spectrum to be filtered and then performing the inverse Fourier transform. An example of a simple filter for suppressing noise is the rotationally symmetric low-pass filter, which has the following transfer function and bandwidth w_0:

$$H(k,L) = \begin{cases} 1 & \text{for } (k^2 + L^2)^{1/2} < w_0 \\ 0 & \text{otherwise} \end{cases}$$

The results of this enhancement contain strong gray-level fluctuations and may not be satisfactory. This problem can be relieved somewhat with the Gaussian low-pass filter. The transfer function in this case is

$$H(k,L) = \exp[-(k^2 + L^2)/w_o^2]$$

where w_o is chosen to provide the minimal mean square error between the enhanced image and the original image.

Homomorphic Image Filtering

This type of filtering has the benefit of local enhancement of contrast by reducing the effect of strongly differing illumination. The process begins by taking the logarithm of the signal f(m,n), which allows separation into contributions from low- and high-frequency components, and then taking the Fourier transform. A transform function such as that presented below is then applied.

$$H(k,L) = \begin{cases} 1 & \text{for } k = O \text{ and } L = O \\ a - (a-b)\exp[-(k^2 + L^2)/c^2] & \text{otherwise} \end{cases}$$

The inverse transform and antilogarithm follow the application of the transform. This homomorphic filtering leads to reduction of contrast in low-frequency image areas and an increase in contrast in high-frequency (fine detail) image areas.

Application of Filters

Faithful digitization of a radiograph may not be possible without the use of enhancement protocols. Filtering of the digitized data, such as with high-pass filters, can be used to enhance the image. The rationale for using high-pass filters is that small details and edges are high-frequency phenomena, while the low-frequency components of the signal provide the overall shading. Film has a great dynamic range, and the low-frequency information often obscures significant details. The high-pass filter reduces the dynamic range, and thus the resulting image should be processed to increase its range for adequate visual presentation. The most straightforward method is to use a linear map of densities based on the minimum and maximum values of the filtered image. This method can distort the true representation, however, because of the preponderance of low-energy information in the radiograph. Histogram equalization is more reliable; an example of this technique uses a frequency-domain filter of the form

$$H(u) = 2(1 - e^{-au})$$

where a is determined by the size of the image and the scanning aperture. This filter has evolved from practical experience and has no theoretical basis.

A problem with any enhancement technique is the production of artifacts (unrealistic information added to the image). Some modification of the filters may reduce the distortions that are characteristic of high-pass filters. A standard (series of holes, grid of lines with varying spatial frequency, etc.) could be used with any digital system to indicate the extent of artifacts produced by the system.

APPENDIX B: PERFORMANCE DEMONSTRATION TESTS FOR THE RADIOGRAPHIC DIGITIZATION PROCESS

Introduction

Performance demonstration requirements for ultrasonic inspections have recently been incorporated into Appendix VIII of the ASME Section XI Code. The concept is based on the fact that effective nondestructive testing (NDT) techniques such as ultrasonic testing (UT) require special skills of the operator and capable procedures and equipment. Studies have shown [1-7] that inspectors using the same equipment and following the same procedure produced a large variation in performance indicating a high variability in interpretation capability from inspector to inspector. Consequently, an effective means to ensure that an inspector can follow a given procedure while using a specific set of equipment is to require that the inspector demonstrate his proficiency in a blind test. The blind test is called a performance demonstration and is based on a statistically designed test to measure performance of the overall system; i.e., the personnel, procedures, and equipment. Since radiography is an NDT technique requiring highly skilled practitioners and good procedures and equipment, it is proposed that a similar performance demonstration should be considered by the ASME Code for qualification of radiography conducted for new work. For this purpose, similar concepts and criteria as developed in the following discussions for qualification of the radiographic digitization process could be used.

For a number of reasons, there is a significant interest in industry to replace the existing radiographic film records with digitized records. The thrust is to digitize the radiographs and to record the digital information on archival storage media such as optical disks. This will overcome the problem of aging of radiographs because digital data should not degrade. However, development of faithful images and correct interpretation of digital information requires: (a) minimum equipment specifications; (b) proper selection and use of image processing techniques; and (c) skills in the use of computers, the controls for displaying information on a video screen, and for the interpretation of digital information. Therefore, a performance demonstration test for the digitization process which includes the procedures, equipment, and personnel is required. The "digitization process" as used in this appendix is meant to encompass all those actions, procedures, equipment, and personnel that are used to digitize radiographic films leading to the faithful reproduction of images that can be properly interpreted with respect to image quality and flaw detection, classification, and sizing. Successfully passing the performance demonstration tests should establish, with high confidence, that the digitization process will faithfully reproduce, reliably detect, correctly classify and accurately size the flaw indications of interest on the radiographic film.

Other sections of this report have discussed equipment specifications and other requirements for the faithful reproduction of radiographic images and have concluded that equipment and technology are available for accomplishing this task. Section 6 of this report on "Implementation" discusses additional requirements and issues related to implementation of the technology and acceptance of the results. These requirements include quality assurance and performance demonstration requirements. Review of the different sections of this report, including the implementation section, indicates that an all-encompassing program is needed for assuring the qualification and acceptance of the overall digitization process. Equipment meeting certain minimum specifications is t[illegible]ed, a quality assurance program established, performance demonstration conducted, etc. The key considerations in developing performance demonstration criteria are:

(1) the requirement to review a statistical sample of the radiographs to be digitized to ensure acceptable quality,

(2) the requirement for "viewing considerations" (on a statistical sampling basis) indicating that the digital image shall be judged by visual comparison to be equivalent to the image quality of the original image at the time of digitization, and

(3) the requirement that the digitization and evaluation of digitized radiographs should be conducted by qualified personnel, procedures and equipment that have successfully passed a performance demonstration.

The intent of the performance demonstration is to show that the digitization process, including the interpreter (evaluator) of digitized images, can faithfully reproduce flaw images of interest that are reliably detected, correctly classified, and accurately sized even when the original film was of acceptable but borderline quality and the flaw indications difficult to evaluate. This would ensure that the digitization process captures the necessary information and that proper image processing functions are used by the interpreter (evaluator) and no important data is lost or masked. Thus the key steps for performance demonstration are to (1) demonstrate capability for evaluating the quality of radiographic film, (2) demonstrate capability for evaluating digitized image quality, and (3) demonstrate faithful image reproduction through reliable detection, correct classification, and accurate sizing of flaws of interest from the digitized film images.

Performance demonstration testing is to be organized to evaluate the overall performance of the digitization process including all the equipment, procedures, and personnel used. It is recognized that different personnel may be used for different functions and each individual needs to qualify only for his specific function(s) within the process. Also, personnel whose involvement in the process is limited, whose knowledge of the technology is not important and whose function would not adversely impact the quality of images produced or on the interpretation of results, need not specifically demonstrate their capability in context of the overall performance demonstration. Once an entire digitization process (equipment, procedures, personnel) has been qualified several times, additional reviewers/interpreters of digitized data can be qualified by performance demonstration by evaluating (detection, classification, sizing) data from films that have already been digitized with the specific equipment, procedures and other personnel (when appropriate) for the particular digitization process. Whenever an essential variable in the digitization process is altered, it is considered that a new process results and this new process must be qualified through a performance demonstration test. The remainder of this Appendix presents information and criteria for developing, conducting and grading the important aspects of performance demonstration for qualification of the overall digitization process.

Objectives for the Performance Demonstration Test

The principal objective for the performance demonstration testing is to assure (with high probability) that a given radiographic digitization process produces faithful images that are correctly interpreted. In other words, processes that produce poor images and/or poor detection, classification, and sizing will have a low probability of passing the performance demonstration tests. The performance demonstration test may consist of four parts: a test of initial film quality, a detection test, a classification test for flaw type, and a sizing test.

Radiographs of Defects for Use in Performance Demonstration Testing

In order to provide guidance as to the types, sizes and locations of defects of interest for performance demonstration, the requirements of the 1989 edition of ASME Section III Code were examined to determine the acceptance standards. These acceptance standards have not changed very much over the years so the current standards can be used to give guidance on the defects to be included in the specimen set for performance demonstration testing.

The ASME code considers welds that are shown by radiography to have any of the following types of discontinuities to be unacceptable.

a. any type of crack or zone of incomplete fusion or penetration;

b. any other elongated indication which has a length greater than:

    1. 1/4 in. (6 mm) for t up to 3/4 in. (19 mm), inclusive;
    2. $1/3t$ for t from 3/4 in. (19 mm) to 2-1/4 in. (57 mm), inclusive;
    3. 3/4 in. (19 mm) for t over 2-1/4 in. (57 mm) where t is the thickness of the thinner portion of the weld;

c. any group of aligned indications having an aggregate length greater than t in a length of $12t$, unless the minimum distance between successive indications exceeds $6L$, in which case the aggregate length is unlimited, L being the length of the largest indication;

d. rounded indications in excess of that shown as acceptable in Appendix VI of the 1989 edition of the ASME Section III Code.

Because radiographs to be digitized can be expected to contain some acceptable indications, which should be faithfully reproduced, and because assurance is needed that unacceptable indications would be properly detected, classified and sized from the digitized images, the specimen set should include both acceptable and unacceptable indications. Areas containing indications of interest will be considered flawed and will be used to determine the probability of flaw detection. The flaw types shall be all of the types listed in the above set of standards. Approximately equal numbers of the Type 1 flaws, cracks, lack of fusion and lack of penetration shall be used and the range of length shall be 0.15" - 2", and in a few cases running the full length of the radiograph. At least 50% of the discontinuities shall be 0.15" ± 0.1" long, 40% shall be from 0.25" to 2" long, and 5-10% shall be still longer (>2"). For the elongated indications, aligned indications and rounded indications, at least 70% of the indications will be > 0.15" up to 0.75", 25% will be between 0.75" up to a maximum of 2" long, and the remaining indications will be longer. The flaw sizes within each sizing range shall be approximately uniformly distributed.

The radiographs produced from specimens containing the above flaws (for the detection, classification, and sizing tests) should be of acceptable quality but provide a challenge to the digitization process. This means that films should meet the requirements for image quality, having high optical density (OD of between 3 to 4) with small contrast changes (delta OD of less than 0.03). Furthermore, for the category 1 type of flaws the crack indications shall be no wider than 0.004" on the film. Before these radiographs are used in performance demonstrations of digitization processes, they must be validated by a group of qualified expert radiographers. The purpose of this validation process is to ensure that the intended indications from the flawed samples are recorded on the films, that the indications can be properly interpreted by expert radiographers and that the indications are approximately of the intended sizes. Further, the expert group should locate, classify, and size the indications on each film to develop a "true state" for the radiographs against which the results of the digitization process are graded.

Concepts for Probability of Detection Tests

The detection performance for the digitization process is described by a probability value called the probability of detection (POD). The POD describes the chances of finding a flaw of a certain type in the digitized radiographs. Effective detection performance is represented by a high POD value for digitized radiographs containing the flaw indications of interest. The simplest objective for this detection test is to assure that the POD for flaws of interest is "high." In order to insure that testmanship is not the cause for detection performance being high, a separate test for false calls will be used also.

In more specific terms, the objective of the test is to pass any digitization process for which the following criteria are met:

- POD > specified acceptable detection probability, for the flaws of interest, and
- FCP < specified level.

In general, the parameters described above quantitatively summarize the objectives of a detection test. These parameters are determined by workmanship considerations and, in general, are based on establishing a reasonably high confidence that flaws can be detected to demonstrate a high quality product has been fabricated. For the digitization process, the parameters are selected to establish with high confidence that for the flaw indications of interest on the film, the digitization process will faithfully reproduce and identify them. In the detection test, radiographs containing the flaw indications will be digitized through the digitization process and in order to pass the test, a minimum number of flaws would have to be detected from the digitized images and have no more than a certain maximum number of false calls.

The number of radiographs with flaw indications and with no indications (blanks) and also the passing grade for detections and false calls are determined from binomial statistical tables. The sample numbers and passing marks are chosen so that an ineffective digitization process (i.e., one with low POD) has a low probability of passing the performance demonstration test, while an effective digitization process (i.e., high POD) has a high probability of passing. The false call test will fail any process having a false call performance higher than a specified level.

Concepts for Evaluation of Sizing Performance

Generally, sizing tests are designed to provide assurance that the NDT measurements can provide estimates of the physical size of defects that are within an acceptable tolerance band of the true size. However, in the case of digitization of radiographic film, the interest is to show that the digitization process faithfully reproduces the film images and that the sizes reported from the digitized images closely match the sizes of the indications on the film. This adds confidence that faithful reproduction has been achieved.

To quantify sizing error, a natural statistic to use is root mean square error, which is defined as the square root of the average of the square of the difference between the true and measured values; in other words,

$$RMSE^2 = \frac{1}{N} \sum_{i=1}^{N} (Measurement_{i} - true_{i})^2 \qquad (1)$$

Root mean square error provides a convenient summary of sizing error because it includes both measurement variance and bias. In fact the relationship is

$$RMSE^2 = Variance + Bias^2 \qquad (2)$$

Therefore, when RMSE is required to be small, both measurement variability AND bias will be small.

Good sizing performance is exhibited by a low RMSE. Therefore, the objective of the sizing test is to fail any digitization process that exhibits an RMSE greater than a threshold value. The appropriate choice for this threshold should be determined by an analysis of the error expected from experts reading the same radiograph and how close the reported sizes need to be to establish faithful reproduction.

To implement the test, a set of radiographs containing *N* flaws are subjected to the digitization process and the sizes reported from the digitized data (images). The flaws should be distributed over the range of applicable sizes. The RMSE capability of the digitization process is estimated using formula (1) and to determine whether or not the sizing test was passed, this estimate is compared to a "passing grade," which is obtained from a chi-squared distribution table. The "passing grade" is chosen so that an ineffective digitization process will have low probability of passing and an effective process, a high probability.

Test Protocol

There are a number of requirements that must be addressed with regard to the development and implementation of a performance demonstration program. The performance demonstration is conducted in a blind fashion which means that the digitization process being qualified is given no information regarding the specimen sets or the flaw indications on the radiographic film to be digitized, with respect to the numbers, types, and sizes present. An independent third party will be present to monitor the performance demonstration test to insure that the test remains blind and that all procedures are followed. The tests are statistically designed to meet specific performance objectives for defining acceptable or passing performance. For the performance demonstration tests, all the films containing category 1 and category 2 flaw indications and blank (films containing no flaw indications) films are presented to the digitization process at the same time. The radiographs will be randomly mixed so that the process (personnel) being tested does not know which category the films belong to.

After the films have been reviewed and the digitized images judged by visual comparison to be equivalent to the image quality of the original image, a random order will be used for presenting the digitized images for subsequent testing since the same radiographs used for visual comparison will be used for flaw detection, classification, and sizing. The process to be followed in the performance demonstration for detection, classification, and sizing of flaw indications is:

- The radiographs are digitized according to specified written procedures, equipment, and with given personnel,
- The digitized radiographs are judged by visual comparison to be equivalent to the image quality of the original image a[illegible] time of digitization,
- The digitized radiographs are reviewed to determine if there are flaw indications in the image (detection),
- The flaw indications are classified as to category 1 or category 2,
- The flaw indications are sized in terms of length, width (for category 1 flaws) and spacing.

From an analysis standpoint, if the digitization process passes the detection portion of the test then, the results are graded in terms of the classification and sizing performance. The width sizing will be performed only for flaws classified as category 1. However, grading of width sizing performance will be conducted only for the cracks in this category. To successfully pass the performance demonstration test, the digitization system must pass all elements (all tests) discussed above.

Application of Performance Demonstration Tests to Digitization of Radiographs

Successfully passing a performance demonstration test is a required step for qualification of the film digitization process. This will include all the procedures, equipment, and personnel that are used to digitize radiographic film and interpret the resulting digitized data. Since procedures can be written in vague terms with many variables, it is necessary to have high confidence limits selected for the tests and to design the tests using conservative assumptions for the indication sizes and the quality of the films. It is reasonable to organize the performance demonstration qualification for the digitization process into a four-part test as described in the following sections.

1. Test for film image quality prior to digitization:

The design objective of this test is to assure with a very high confidence level that the radiographers, who are responsible for reviewing the radiographs prior to digitization to ensure acceptable quality, can discriminate between acceptable quality and unacceptable quality radiographs. The specific objective for this test is to assure that the radiographers' decision for classifying film image quality is correct at least 97% of the time with a 95% confidence level. Table 1 shows the sample sizes and the pass/fail criteria for this test. To conduct the test, radiographs would be selected so that approximately 25% are clearly of acceptable quality, approximately 25% are clearly of unacceptable quality and approximately 50% are of borderline quality. For grading this test the "true" state of a radiograph's quality would be determined by using densitometer readings and input from a number of knowledgeable radiographic experts. If an interpreter had a performance level for a given set of N radiographs that is less than the number shown in this table, then the interpreter would fail the test.

Table 1. Sample Sizes for a Radiograph Quality Test

Sample Size	Pass/Fail Criteria 95% Confidence Level
150	150
157	156

2. Detection test:

The objective of the performance demonstration test for detection is to assure with high confidence that the digitization process will produce a high probability of detecting the flaw indications of interest. The POD will be evaluated for two different categories of discontinuities. The first POD test will consist of category 1 type discontinuities that are cracks, incomplete fusion and incomplete penetration. The sample set for category 1 shall include approximately equal numbers of the 3 different type discontinuities in the category. The second test will be for category 2 type discontinuities and include elongated, aligned and rounded indications. The sample set for category 2 shall consist of 40% for elongated indications, 40% for aligned indications and 20% for rounded indications. Table 2 depicts the threshold probabilities and confidence levels for these 2 tests of category 1 and 2 type discontinuities that the digitization process has to equal or exceed in order to successfully pass the test. The test is designed such that a digitization system whose true performance exceeds the number in the table will have a high probability of passing the test and if the true performance is less than the value in the table it will have a low probability of passing the test.

Table 2. Detection Test Design

Discontinuity Type	Acceptable POD Threshold	Confidence Limit
Category 1 cracks, incomplete fusion and penetration	95%	95%
Category 2 elongated, aligned and rounded indications	95%	95%

For the target POD threshold and specific confidence level the data in Table 3 provides the listing of the sample sizes needed and the pass/fail criteria for both the category 1 and category 2 type discontinuities. For a performance demonstration the total number of samples in the set will include the number for the category 1 plus the number needed for the category 2 test. For example, 93 category 1 and 93 category 2 samples would be needed for a total of 186 samples with one non-detection being allowed for each category 1 and category 2 flaws.

Table 3. Sample Sizes for a Detection Test

Sample Size	Pass/Fail Criteria Category 1	Category 2
59	59	59
93	92	92
124	122	122

To guard against testmanship, a false call rate >10% is considered unacceptable. A sufficient number of radiographs need to be included in the sample set to be digitized in order to adequately estimate the false call probability (i.e., 30 to 40 radiographs). These radiographs shall contain no flaw indications.

3. Flaw type classification test:

The flaws that are detected from the digitized data shall be classified as either category 1 or category 2. Consequently, the test will be evaluated by assessing misclassification errors associated with the classification scheme. The two probabilities that describe these errors are:

- Probability of correctly placing category 1 flaws in classification 1,
- Probability of correctly placing category 2 flaws in classification 2.

Good classification performance would be based on having high values for both of these probabilities. Table 4 describes how this test is structured. The same set of radiographs will be used for both the detection test and the classification test. The detection test is associated with detecting an indication while the classification test concerns the correct classification of the detected flaws into category 1 and category 2 classifications. The numbers from Table 3 are then used for the pass/fail criteria. If a test was designed for no misses then all flaws must be classified correctly and if the test was designed

Table 4. Sample Size for Correct Flaw Classification

Discontinuity Type	Acceptable Classification Level	Confidence Limit
Category 1	95%	95%
Category 2	95%	95%

for one miss for detection then one misclassification is also permitted.

4. Flaw sizing test:

Evaluation of flaw sizing accuracy will be conducted with the RMSE and the values of performance that have been selected are shown in Table 5.

Table 5. Flaw Sizing Test Design

Size Range	Acceptable RMSE Threshold	Confidence Level
0.15" - 2" and > 2"	0.1"	95%

The design is constructed to use the same flaws for detection and sizing. The evaluation of performance is the RMSE, and the smaller the size of the sample set, the smaller the acceptable threshold will need to be in order to account for measurement error. Table 6 shows a list of passing RMSE values as a function of the sample set size for an RMSE threshold of 0.1".

Table 6. Flaw Sizing Sample Set Design of Passing RMSE Value for an RMSE Threshold of 0.1"

Sample Size	Passing RMSE Value for RMSE Threshold of 0.1"
118	0.089"
180	0.091"
200	0.092"
220	0.092"
250	0.093"
300	0.093"

As an example, for a total of 118 flaws that are equally mixed between category 1 and category 2, the corresponding RMSE threshold (from Table 6) is 0.089". This means that the measured value in the test must be less than or equal to this value in order to successfully pass the test.

In addition, the category 1 flaw indications from cracks that have a maximum width of 0.004" on the radiograph, are required to be sized in this width dimension to ± 0.002".

Recommendations

There are a range of tests that are shown in the tables in this section. The size of test that is recommended will be the ones where there can be at least one error that can be made while taking the test. These tests normally have larger sample sizes but they estimate performance more accurately than smaller tests and they will have a higher pass rate for effective digitization processes.

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APPENDIX C:
UNITED STATES NUCLEAR REGULATORY COMMISSION
GENERIC LETTER 88-18;
PLANT RECORD STORAGE ON OPTICAL DISKS

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

October 20, 1988

TO: ALL LICENSEES OF OPERATING REACTORS AND HOLDERS OF CONSTRUCTION PERMITS

SUBJECT: PLANT RECORD STORAGE ON OPTICAL DISKS (GENERIC LETTER 88-18)

The NRC has been requested by two utilities and an NSSS supplier to approve the use of optical disk document imaging systems for the storage and retrieval of record copies of quality assurance records. The purpose of this generic letter is to inform addressees that the staff approves the use of this method of record keeping when appropriate quality assurance controls are applied.

Appendix B of 10 CFR 50, under criterion XVII, "Quality Assurance Records," establishes requirements for a record keeping system, and chapter 17 of the Standard Review Plan (NUREG-0800) expounds on these requirements. The purpose of the record keeping system is to ensure that records are available when needed. ANSI N45.2.9-1974, "Requirements for Collection, Storage, and Maintenance of Quality Assurance Records for Nuclear Power Plants," as endorsed by Regulatory Guide 1.88 (Rev. 2) and Basic Requirements 17, Supplement 17S-1, and Appendix 17A-1 of ANSI/ASME-NQA-1 1983 edition, "Quality Assurance Program Requirements for Nuclear Facilities," as endorsed by Regulatory Guide 1.28 (Rev. 3) both describe quality assurance controls regarding records. Appropriate quality controls for an optical disk document imaging system include the following:

- The optical disk technology does not allow deletion or modification of record images.
- The image of each record is written onto two optical disks.
- The legibility of each record image is verified to ensure that the image is legible on both disks. If the image is illegible, the hard copy record is maintained as the record copy.
- One optical disk is stored in the document imaging system for on-line retrieval.
- The second (backup) optical disk is stored in a records storage facility meeting the requirements of ANSI N45.2.9-1974 for single copy storage or in a separate remote location.
- To ensure permanent retention of records, the records stored on an optical disk are acceptably copied onto a new optical disk before the manufacturer's certified useful life of the original disk is exceeded. This includes verification of the records so copied.
- Periodic random inspections of images stored on optical disks are performed to verify that there has been no degradation of image quality.
- If the optical disk document imaging system in use is to be replaced by an incompatible new system, the records stored on the old system's disks are acceptably converted into the new system before the old system is taken out of service. This includes verification of the records so copied.

Contact: J. Spraul, Performance & Quality Evaluation Branch
(301) 492-1021

8810250164

Licensees using optical disks for record storage should notify the NRC in an updated FSAR per 10 CFR 50.71(e) or by letter per 10 CFR 50.4(b)7. License applicants should notify the NRC in the SAR per 10 CFR 50.34.

Sincerely,

Gary M Holahan for

Dennis M. Crutchfield
Acting Associate Director for Projects
Office of Nuclear Reactor Regulation

NRC FORM 335
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U.S. NUCLEAR REGULATORY COMMISSION

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This report contains a review and evaluation of the technology, equipment, and codes and standards related to the digitization of industrial radiographic film. The report presents recommendations and equipment-performance specifications that will allow the digitization of radiographic film from nuclear power plant components in order to produce faithful reproductions of flaw images of interest on the films. Justification for the specifications selected are provided. Performance demonstration tests for the digitization process are required and criteria for such tests is presented. Also several comments related to implementation of the technology are presented and discussed.

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