X-RAY TELEVISION INSPECTION OF AEROSPACE WELDMENTS

TELEVISION X-RAY IMAGE ENLARGEMENT SYSTEM FOR INSPECTION OF AEROSPACE WELDS

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SUMMARY

A sensitive new television X-ray image enlargement system has been developed under sponsorship of Watertown Arsenal Laboratories (Army Materials Research Agency) by the Department of Welding Engineering of The Ohio State University. Now commercially-available through Philips Electronics Instruments (Norelco), complete systems have been in service since January 1963 in aerospace, electronic, and other facilities. Such users report highly-satisfactory performance and unusual reliability in service. The new X-ray system permits in-motion or stationary examination of critical aerospace materials, components, and systems such as sheet materials, weldments, brazed joints, electronic components, printed circuit assemblies, small mechanisms, and biological specimens.

The television X-ray image enlargement system employs special combinations of beryllium-window X-ray source and beryllium-window television camera tubes which respond directly to X-radiation without intermediate conversion into light. Images from the 3/8 by 1/2 inch sensing area of the input vidicon are enlarged by thirty or more diameters and displayed remotely on full-size television picture tubes. Detail resolution exceeds 10 microns (390 microinches). Image contrast can match or exceed that of high-contrast, fine grain films. In-motion inspection can proceed at rates of one foot per minute at the test object (30 feet per minute or 6 inches per second at the output monitor) without image blurring due to lag effects. Penetrameter sensitivity permits visualization of the 1-T hole in two percent penetrameters on test objects in motion, within the design range of the equipment. Such 1.4 per cent penetrameter sensitivities have been obtained with aluminum alloys up to one inch in thickness, and with steel up to one-quarter inch in thickness, with test objects in motion. With new techniques of integration of X-ray images, these performance limits have been more than doubled, in electronic radiography of stationary test objects. Other recent advances have considerably improved system performance characteristics.

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INTRODUCTION

Aerospace and nuclear developments employing materials and components under severe service conditions have placed new requirements upon nondestructive testing. Minute discontinuities can become highly-critical stress-raisers in materials under high applied stress, or can limit service life under high-temperature or corrosive environments. High-resolution, detailed inspection for material discontinuities, welds and joints, and assemblies is required to detect undesired materials and impurities; cracks, voids, and segregations; variations in structure and composition; failures during manufacture or service; and other conditions. Inspection of densely-packed, miniaturized electronic and electromechanical components in critical assemblies can also be of great importance in assuring reliability of guidance and control systems. Previously-available nondestructive test methods are often inadequate for these new applications, and rarely can be applied for dynamic analysis of the motion of system components. Systems for enlargement of image detail, with capabilities for high-speed inspection combined with high sensitivity to critical material and assembly conditions, are needed. One such system, now commercially available and in service in aerospace and electronic industries, is the television X-ray image enlargement system described in this paper.

COMPONENTS OF TELEVISION IMAGE SYSTEM

The television X-ray image enlargement system developed at The Ohio State University under sponsorship of Watertown Arsenal Laboratories includes the following basic system components:

1. Constant-potential, beryllium-window, dual-focus, high-output X-ray equipment operable from 25 to 150 kvp.

2. Specimen-positioning and traversing mechanism with remote control, for locating and moving test objects between X-ray source and television input camera unit.

3. Modified, high-quality vidicon television camera with special X-ray-sensing vidicon camera tube (manufactured to project specifications), designed to provide high-detail and contrast sensitivities to direct X-ray input images, and to withstand high radiation levels. This unit must provide uniquely high signal-to-noise ratios since its output video signals are often one hundred times smaller than those normally produced by light-sensing television cameras.

4. Dual-channel, high-quality closed-circuit television camera chains which amplify camera output signals, generate synchronizing pulses, and distribute output signals to one or more viewing monitors where remote inspection occurs. In the Ohio State University research, numerous modified systems have been developed, including (a) slow-scan systems, (b) intermittent-scan systems, (c) scan-converter systems, (d) contrast- enhancement systems, (e) memory systems, and (f) larger input image area systems. Each such system permits considerable improvements in performance characteristics, some of which are described later.

5. Multiple monitors providing enlarged, high-detail images remote from the radiation hazards of the X-ray exposure area, providing complete X-ray safety to inspectors. Output signals are compatible with commercial broadcast television systems, and have been recorded and played back through video-tape recorders with excellent image quality. Thus, inspection records can be provided, and reproduced locally or at great distances whenever desired.

Throughout this research, the overall system--X-ray source, test-object manipulation, vidicon camera tube, television signal systems, and display and recording systems--has been engineered for optimum overall characteristics. Such performance capabilities have not been attained by incompetently-engineered systems in which the X-ray-sensing vidicon camera tubes developed in this research have been inserted into commercial closed-circuit television chains, without regard for the basic principles underlying the overall system designs.

X-Ray Source Equipment

Considerable importance is attached to the selection of optimum X-ray equipment to provide high-contrast, highly-detailed test-object images to the television camera. Numerous types of X-ray equipment are available commercially, most of which are inappropriate for use in high-sensitivity X-ray image systems. Primary requirements include: (a) extremely high radiation output, preferably well above one-half million roentgens per minute at the detector, (b) extremely low inherent filtration, in order that maximum contrast can be provided in the X-ray image after the beam passes through the test material, (c) automatic control to permit operation at the maximum feasible radiation output throughout a wide range of X-ray kilovoltage settings, with continuous potential adjustment without tap-changing, and (d) fractional focus target areas, to provide image sharpness adequate to resolve ten micron or smaller details of discontinuities in the test materials. These requirements have been met in this research by selection of a

Norelco M-G 150 beryllium-window, constant-potential X-ray source with outputs of 600,000 roentgens per minute over the range from 100 to 150 kilovolts, constant potential. In three years of service, often almost continuously for eight hours a day, this equipment has provided uninterrupted operation without failure or deterioration of any type to date. Experience with this system indicates the desirability of high-output, beryllium-window sources with fine focal spots (less than one millimeter), operating at constant potential, with continuous duty cycle ratings.

On the other hand, numerous tests have also been made with nearly all types of X-ray source equipment commercially available in the United States, with little or no success. In all cases tested, sources with glass-window X-ray tubes, and/or filtration of the emergent beam through insulating oil, plastic, or metal housings, have resulted in severe reduction of X-ray image contrast. Even with one-quarter inch of steel as test material, no success has been attained to date in achieving true two-per cent penetrameter sensitivities with any glass-window systems, whereas such contrast sensitivities are readily obtained with the source selected for this research. In addition, all sources tested which had other than constant-potential waveforms (half-wave-rectified systems, Villard circuits, and others providing pulsating X-ray output) have been found to be inadequate, both in X-ray output and in image contrast. Particularly unsuitable have been high-frequency X-ray sources tested to date, which produced gross interference with the output video images (such as moving white bars or areas of no image information, and extremely poor signal-to-noise ratios in the television system images). All normal causes of interference, such as magnetic fields, electric fields, coupling between X-ray source cables and television system cables, have been eliminated in these tests of pulsating sources. The basic difficulty appears to arise from the actual pulsating nature of the X-ray beam itself, which creates transient ionization of high magnitudes within the television camera circuitry. With each X-ray pulse, intense ionization occurs in the camera enclosure. These ions are then attracted to exposed leads and circuit components, injecting strong spurious signals which overwhelm the video signals related to the X-ray image itself. Even when all free air spaces have been eliminated, similar effects result in the solid dielectric materials (insulation and capacitors) whose conductivity changes with X-ray irradiation. Thus, truely constant-potential X-ray sources provide numerous basic advantages in television X-ray image systems. Shielding, of the magnitude of 1/4 to 1/2 inch of lead, to reject radiation from the camera enclosure, has also been tested, with little success, in an effort to eliminate these ionization effects. Radiation still passes into the camera through the vidicon tube itself, and thick shields force the camera tube (with its focussing and scanning coils) to be mounted at a considerable distance from the test object, so that image sharpness is considerably deteriorated by the increased test-object to detector spacings.

During in-motion inspection, the television X-ray system makes a complete X-ray exposure each 1/30 second. This totals to 1800 separate exposures each minute. Each exposure may require from 1/50 to 1/10 of a roentgen (X-ray film exposures usually require perhaps 1/10 to 2 roentgens and an exposure of the order of minutes with continuous-duty X-ray sources). Thus, the X-ray beam passing through the test material must still retain an image-forming intensity of the order of 35 to 300 roentgens per minute to excite the vidicon camera tube to optimum signal levels. X-ray attenuation in the test material can often be of the order of 10 to 1000 (the ratio of incident to transmitted X-ray beam intensities). Thus, it is essential to provide high radiation output from the X-ray source, and to utilize short source-detector distances. Radiation intensities at the vidicon detector are subject to an inverse-square law, so that beam intensity diminishes rapidly with increasing distance between X-ray target and television camera. Short distances, of the order of 5 to 10 inches, are usually found most effective, with fractional focus tubes. With larger focal spots, these distances must be increased to retain image sharpness, with resultant reduction in signal levels and loss of image quality. It is particularly important that the X-ray tube housing permit close spacings between source and test material. Many tank-type X-ray units, with the X-ray tube centered within the transformer, and other units with considerable spacing between target and port, prohibit use of short source-object distances, and so prove unsuitable.

The most critical factor in selection of X-ray source and kilovoltage, in addition to radiation intensity, is the resultant test-object gamma or output image contrast factor. In a typical case, the true input signal is a change in test-object thickness or density (caused, for example, by a discontinuity or segregation). The output signal from the test object is the variation in transmitted X-ray intensity caused by the local thickness or density change. The test material contrast factor, γ_m, is the ratio of the change in output radiation intensity, $\Delta I/I$, to the change in thickness or density which caused it, namely, $\Delta x/x$ or $\Delta\rho/\rho$:

$$\gamma_m = (\Delta I/I)/(\Delta X/X) \quad \text{or} \quad (\Delta I/I)/(\Delta\rho/\rho) \tag{1}$$

Extensive test experience indicates that the X-ray source and spectral characteristics must provide a test material gamma, γ_m, of the order of unity or higher, if adequate image contrast to reveal two per cent penetrameter sensitivity is to be attained with television X-ray image systems. This is the most important basic requirement in selection of X-ray sources for television image enlargement systems. The X-ray source must provide both high-intensity radiation output and test material gamma values exceeding unity, for the material to be inspected, for optimum performance. Very few radiation sources presently available can meet these requirements.

Specimen-Handling Equipment

Test objects that can be profitably inspected with the television X-ray image enlargement system can be of many different sizes and shapes. Size can range from large missile cases, in which longitudinal or girth welds must be inspected, to semiconductor devices and diodes perhaps 1/16 inch in diameter and 1/4 inch in length. Thus, specimen positioning and scanning equipment must, in general, be designed for the specific test objects to which it will be applied. However, since the practical inspection rate is determined not by equipment limitations, but rather by the rate of examination and evaluation of an individual inspector, it must be possible to vary the rate of motion. Typical inspection rates can vary from 18 inches per minute to stand-still (while the inspector examines a particular discontinuity in detail). Since the test-object motion provides a pseudo-stereoscopic view at several possible angles through the test object, relative motion of test object and camera or X-ray source in two lateral directions is always desirable. With small objects, such as electronic components, transistors, and small-diameter tubes, it is often helpful if the object can be rotated to provide views at many angles, in addition to longitudinal and lateral traversing. Speeds of movement should be infinitely variable, even at creeping speeds, in any direction of motion, to meet inspector requirements in critical inspection. Simplified traversing equipment has been used in the basic research, and a very effective traversing system for small and medium-weight components is commercially available with the Philips X-ray image enlargement system.

Inspection experience with television X-ray image enlargement systems demonstrates considerable advantages in viewing test objects in motion, rather than stationary. The eye detects and responds with much greater sensitivity to moving areas of small density differences than to the same images when stationary. In fact, motion makes clearly visible faint images of discontinuities that appear almost invisible with stationary objects, particularly where signal levels fall below noise levels in the inspection system. What is required is relative motion between X-ray source, test object, and television camera, so that discontinuity images move on the screen of the television picture tube. Such relative motion can be produced by motion of any of the three system elements (source, test object, and camera). In some cases with stationary test materials, slight oscillation or circular motion of the X-ray tube alone provides the desired motion in the output image, increasing inspection sensitivity.

Television Camera and X-Ray Vidicon

The television camera unit and X-ray-sensing vidicon camera tube are the most critical elements in the entire signal chain used in television X-ray image enlargement systems. The energy in the X-ray image signal transmitted through the test material during each 1/30-second frame interval is exceedingly small. After direct conversion of this input signal to a video signal in the vidicon, without intermediate conversion into light, the video signal levels are of the order of a fraction of a millimicroampere (10^{-9} amperes). When this vidicon output current flows through the load resistance, the video voltage signals have a maximum amplitude of the order of 50 microvolts, at best. Exceedingly good signal-to-noise ratios, of the order of 200 db, are needed at this critical point in the signal system. Such a decibel ratio implies, by definition, a ratio of 10^{10} between signal and noise voltages. Thus, noise levels must be uniquely low, as compared with noise levels acceptable in most types of electronic equipment. The X-ray sensing vidicon tubes, designed and manufactured to project specifications, provide the desired signal-to-noise ratios. However, the load resistor and input circuit to the preamplifier must be designed with optimumly-selected components and band-widths to avoid introduction of excessive noise levels. Since X-radiation photons passing through components of the input network can produce noise (by sudden showers of electrons producing ionization and variations in resistance), intelligent design and careful construction are quite essential at this point. Exposed leads from the signal ring of the vidicon to the input network can also serve as collectors for air ionization (produced by the incident X-ray beam as in any ionization gauge), injecting noise signals of intolerable amplitudes. In this research, and in equipment produced commercially under license from the University with design consultation by the research investigators, these factors have been controlled effectively. The result is a remarkable clarity of X-ray television images, not achieved by indiscriminate attempts to insert the X-ray-sensing vidicons into commercial closed-circuit television chains.

Particular care is required if semiconductor devices are introduced into portions of the television camera circuitry subjected to high radiation levels. As is well known from nuclear and aerospace system developments, exposure to ionizing radiation can produce deterioration or failure of some semiconductor components. With input radiation levels as great as one-half million or more roentgens per minute, continuous operation for lengthy time periods (such as years) results in fantastic levels of irradiation. Intelligent circuit design and selection of components is required if long life serviceability is to be built into television X-ray image enlargement systems. Careful advance consideration of these factors has resulted in systems that have operated with no such failures for more than two years in research, and for nine months (since their initial installation) in the case of commercial models manufactured under license, in aerospace facility installations. Since it is anticipated that X-ray systems of this type will be used in continuous process monitoring in fusion welding, brazing, assembly, and other operations, continuity of trouble-free service is an essential requirement.

Closed-Circuit Television Chain

High quality is also essential throughout the entire closed-circuit television chain from camera to monitor. Signal integrity must be preserved through extensive amplification and modification, in the presence of synchronizing and control signals. Here, again, signal-to-noise ratios are of utmost significance. Because signal levels are often orders of magnitude smaller than the signal levels used in light-sensing television systems, noise must be controlled or eliminated wherever possible. Signal range and contrast are also of great importance, since X-ray images can involve signal ratios far exceeding 1000 to 1, yet small changes of contrast must be clearly delineated at any level in the entire signal range. Final image quality is far more dependent upon preservation of excellent signal-to-noise ratios, signal range without distortion, and high signal contrast than upon the usual factors of number of lines and bandwidth of the system. In fact, it has been impossible, to date, to discover test objects or artifacts with detail so fine that it could not be readily resolved, even with 525-line frames (1400 lines to the inch), in this research. Thus, so-called high-resolution television chains used for light-sensing applications do not represent optimum system designs for critical X-ray inspection systems. However, in the commercial equipment manufactured under University supervision and license, 675 line frames have been used quite successfully, and larger numbers of lines per frame can be supplied when required for industrial applications. High numbers of lines per frame involve two unfortunate results: (1) the signal levels are lowered since smaller target areas contribute to each signal element, and (2) high band-width electronic signal chains pass greater noise levels. Consequently, systems with unnecessarily-large numbers of lines per frame inevitably result in lowering of the already-critical signal-to-noise ratios, and actually produce lower-quality output images.

Commercial television systems often include signal-compression or contrast-reduction in their transfer characteristics. Such loss of image contrast is not acceptable in X-ray image systems, where all available contrast is needed. In fact, contrast amplifiers have been designed for use in the research system and, under optimum conditions with high input signals, can multiply contrast by factors adjustable from 0.5 to 5 or 10. However, as noted later, the present linear system offers such high overall contrast that few occasions have been found where additional contrast amplification was required.

Recently, the research television amplifier chain has been modified to permit continuous reproduction from a single-frame input exposure of any desired length. With this system, flash radiography becomes feasible. In addition, X-ray exposure required for image reproduction can be enormously reduced, if desired. Excellent images of a 400-mesh wire screen have been obtained from a 10-watt, 5-kvp. microradiographic X-ray source, and from longer exposures at an input radiation intensity of 0.0005 roentgens per minute. Contrast sensitivity has been so enhanced with the modified system that 1-T penetrameter holes in two per cent penetrameters have been seen through 1/2 inch of steel exposed at 130 kvcp. Good images have been obtained of copper segregation areas in 2024 aluminum alloy spotwelds, as well as of the dark ring delineating the nugget boundary, and of geometric defects such as cracks. Slow-scan television inputs can also be utilized with the modified system, resulting in reduction of X-ray inputs by factors of 5 to 10 times, depending upon the scan rates utilized. Ten-micron wires can be clearly visualized with each of these system modifications. Other modifications now under evaluation show promise of further system improvements to provide greatly increased image enlargements.

Output Monitors and Picture Tubes

Professional-quality output monitors with 17 and 21 inch diagonal picture tubes are employed to present the enlarged television X-ray images to the inspectors. Larger monitors could be used, but add little to the image information. Image non-linearity due to screen curvature is minimized with the 17 and 21 inch picture tubes, as compared to larger sizes. Images can be presented either as negatives (similar to X-ray film images) or as positives (similar to fluoroscopic screen images). In the commercial version of the system manufactured by Philips, images can be further enlarged by a push-button control, for examination of specific image areas. If desired, images can be readily recorded on each of several types of video-tape recorders presently available, with little loss of image detail and information. A research modification has also permitted recording of video images by means of a modified audio tape recorder, with relatively good performance. Monitor images are also routinely recorded with synchronous motion-picture cameras, with some consequent loss of image detail and contrast.

Monitor viewing is most satisfactory if ambient lighting can be continuously controlled from the operator's station, to match the screen brightness levels and to avoid glare. In addition, experience indicates that eye fatigue from glare, and sensitivity to small contrast variations, is improved by avoidance of very high brightness areas in the screen images.

By polarity reversal, such bright images can be reversed to dark areas, in accordance with viewer preference. Masking of small test objects (where the unfiltered X-ray beam passes around the periphery of the object to illuminate the surrounding screen areas) can also be used to eliminate glare. Monitor brightness and contrast controls also provide additional means of controlling image quality to suit inspector preferences.

PERFORMANCE CHARACTERISTICS OF SYSTEM

The performance characteristics of the X-ray television image enlargement system can best be defined in terms of factors such as:

1. X-ray kilovoltage range.
2. Material density and thickness ranges.
3. Rates of test object motion.
4. Detail resolution in enlarged images.
5. Contrast in enlarged images.
6. Penetrameter sensitivities attainable.
7. Reproducibility of performance.

In each of these performance characteristics, the research system appears to match or exceed the capabilities of X-ray film radiography with high-contrast, fine-grain X-ray films, in so far as comparisons have been completed to date.

X-Ray Kilovoltage Range

Excellent images have been obtained with beryllium-window X-ray tube sources and beryllium-window vidicon tubes over the kilovoltage range from 3 to 300 kvp (the limits of equipment available to date in this research). Fair images, of reduced contrast, have also been obtained with glass-window X-ray sources and glass-window X-ray tubes in the range from 50 to 400 kvp. It is believed possible that higher-voltage sources could be employed, if radiation levels are adequate, and inherent filtration is not excessive.

Material Density and Thickness Ranges

Excellent images have been obtained with beryllium-window X-ray tubes and vidicons with all low-density or thin-gage materials, and with aluminum and other light alloys up to one inch of thickness. Steel up to 1/4 inch in thickness can be accomodated with the in-motion inspection system, and up to 1/2 inch in thickness with the stationary system. Good performance has been obtained with light alloy castings, plastics, fiber glass laminates, cloth, stainless steels, Inconel, and dense refractory alloys (in thin sections).

With commercial aluminum alloys, excellent image quality is obtained up to one inch of material thickness during in-motion inspection. With the use of the scan-converter system for enhancement of stationary images, aluminum alloys up to three inches in thickness have been examined successfully. The criterion of successful imaging has been the visualization of the 1-T hole in two per cent Mil 271 type penetrameters, in each case.

Rates of Test-Object Motion

The X-ray television image system is capable of presenting useful images (100-mesh wire screen clearly resolved) with rates of test-object motion up to 18 inches per minute. With 30-diameter enlargement of the output monitor images, these rates correspond to speeds of 45 feet per minute as the output image moves across the viewing screens. Few, if any, observers can perceive the detail in images moving at this speed, particularly with complex test objects. Thus, the speed of viewing with in-motion X-ray examination is limited by the observer' s visual acuity and speed of reaction, and by the nature of the test object and the number and type of discontinuities to be evaluated. Practical experience shows that inspection of nearly-perfect weldments can sometimes be carried out at rates of 6 inches to one foot per minute (in zones where no unusual details require longer observation). However, the usual practice is to permit the inspector to control the rates of motion continuously during inspection. The typical inspector may move the test object at relatively rapid rates in areas where no discontinuities are observed. When a discontinuity indication passes across the screen, the typical inspector stops the motion in order to examine the indication in greater detail. Where indications are faint, and tend to merge with background mottling or other image structure when stationary, the detailed inspection is carried out with slow movements of the test object. Slow oscillation of the X-ray tube, test object, or television camera, in either a straight line or in a circle, provides the desired relative movement of test-object discontinuity images on the background of noise or mottling that is visible with inadequate signal levels. In general, preferred rates of motion of the test object are in the range from one to twelve inches per minute, in routine inspection of simple specimens. In the case of complex electronic assemblies or printed circuits, on the other hand, the inspector may examine each individual component in detail, and follow each circuit connection to verify its continuity. When inspecting fine networks of cracks, or soldered connections for cold-soldered joints with thin oxide films surrounding the conductors, very careful alignment of the X-ray beam with the plane of the discontinuities can reveal far more information than any single arbitrary view. Such continuous variation of X-ray beam angulation can provide far more information than a limited number of film radiographs at different angles, in evaluation of cracking and other fine, oriented details of test object discontinuities.

Detail Resolution in Enlarged Images

The fineness of details resolvable in the enlarged output images of the X-ray television system is a function of parameters such as (a) the geometric unsharpness of the X-ray image projected onto the target of the vidicon camera tube, (b) the input radiation signal level, (c) the test-object contrast, (d) the signal-to-noise ratio attained in the overall television system, and (e) the number of scanning lines per inch in the input image area (horizontal and vertical resolution characteristics of camera tube and system). Of these variables, the least important in practice is the number of scanning lines per frame of image. (This is at variance with common experience with light-sensing television systems, where so-called high-resolution systems often employ from 675 to 1125 or more scanning lines per frame.) For example, with 525 scanning lines in the 3/8-inch input image height, the number of lines per inch is nearly 1400. With 1125 lines in the same input image height, the number of lines per inch can be increased to about 3000 lines per inch. However, with the 525-line system, or the 675-line system commercially available, no difficulty has been encountered in clearly delineating the finest wires so far attainable, of 10-micron or 390-microinch diameter. Other tests have indicated that 1/10,000-inch detail can be seen clearly. The finest detail so far available has been in the internal organs and appendages of small insects, where the movements of body fluids, or of ingested fluids, could be visualized clearly. On one occasion, the birth of 42 larvae from a fly was observed in detail, including the birth process of each individual larva and its movements across the screen after birth. More recently, tests have been made to observe the feeding of live mosquitoes from the tail of a mouse, including the passage of blood through the oral passages of the mosquito to its stomach (which incidentally fills from the rear forward). No commercial test objects have yet been found in which detail resolution could not reveal the smallest known discontinuities, if adequate contrast and signal level could be provided for normal imaging.

Of much greater significance in revealing fine discontinuities in industrial test objects is the ability of the image system to reveal detail through thicker materials, where test object contrast is limited, and the discontinuities extend through only a fraction of the material thickness. In this case, the image contrast is critical to detail visibility. Image contrast is not enhanced, but rather is lost, by use of an excessive number of scanning lines. This loss is related to (a) reduced input signal levels, and (b) poorer signal-to-noise ratios inherent in extremely wide-band signal systems. The contrast in the X-ray image is also a function of the radiation quality (or spectral characteristics) since, in general, contrast is increased as X-ray kilovoltage is decreased (longer wavelength X-rays). Thus, any loss in system signal-to-noise ratios forces use of higher X-ray kilovoltages to increase signal levels above noise limits. The resultant loss of contrast can make fine details invisible to the eye since they do not vary sufficiently from background illumination levels to be visible. Geometric unsharpness in the X-ray beam image transmitted to the input camera also deteriorates image detail, just as it does in the case of film radiography. With the short source-detector distances required to attain adequate signal levels, this factor can become of great significance in detail resolution. With thin test materials located close to the vidicon target, a ratio of l/d (distance of source from detector to distance from top surface of material to detector) can be readily held above the usual 20/1 or 10/1 ratios considered desirable in radiography. However, when test object thickness exceeds one-quarter inch, or the object must be separated from the vidicon camera because of its shape or handling considerations, unsharpness considerations can be critical to detail resolution.

The final factor of critical importance to detail resolution is the absolute level of input X-ray intensities transmitted through the test material to the vidicon target. The higher this signal level can be made, the better the attainable signal-to-noise ratios in the output image. As the inherent noise of a television system is relatively constant, once the minimum noise levels have been attained, the only practical way to improve signal-to-noise ratio is by increasing the input signal levels. Thus, short source-detector distances (within acceptable limits of geometric unsharpness in the X-ray image) permit increasing the input signal levels by the inverse-sqaure law, whereas unsharpness increases linearly as the source-object distance is reduced. This situation is analogous to that of ensuring exposure levels sufficient to surpass the inherent fog level, in film radiography.

Contrast in Enlarged Images

Adequate contrast is essential in the enlarged output images of the television X-ray image system, if images are to be visualized. Tests in both X-ray film viewing and in television image viewing suggest that a practical requirement for visibility under industrial inspection conditions is a brightness difference of the order of five per cent (a film density difference of 0.02 H & D corresponds to a brightness differential of about 4.72 per cent). The large area contrast sensitivity of film radiography can be determined as:

$$\%C = \%(\Delta x/x) = 4.72\%/\gamma_m \gamma_f \qquad (2)$$

where:

$\%C$ = Per cent large area image contrast (thickness).
Δx = Minimum detectible change in material thickness.
x = Total thickness of test material.
γ_m = Test material contrast (See Eq. 1).
γ_f = Film gradient or contrast factor.

With high-contrast X-ray films exposed to densities in the range of 2 to 4, the film gradient, γ_f, can be as high as 4 to 7. Thus, direct film radiography can provide remarkably high image contrast, and large-area contrast sensitivities of the order of one to two per cent are often required in industrial radiographic inspection.

The corresponding relationship for the X-ray television image system is:

$$\%C = \%(\Delta x/x) = 4.72\%/\gamma_m \gamma_v \gamma_a \gamma_k \qquad (3)$$

where:

γ_v = Contrast factor of vidicon camera tube.
γ_a = Contrast factor for electronic amplifier chain.
γ_k = Contrast factor for kinescope picture tube.

Each such contrast factor is the slope of a transfer curve, relating the logarithm of the output signal to the logarithm of the input signal (similar to the film gradient, which is the slope of the film characteristic curve that relates density (a logarithmic function) to the logarithm of exposure). For the television image system, γ_v = 0.4 to 1.2 dpending upon the type of vidicon target and operating conditions. The amplifier contrast factor for conventional light-sensing television chains is often reduced to the order of 0.5 to 0.7, but may be unity. For the X-ray television system, the contrast factor of the amplifier chain can be made 1.0 to 10 or larger, if desired. The picture tube or kinescope usually has a contrast factor of the order of 2.0 to 3.0. In combination with beryllium-window X-ray sources and vidicon tubes, the Ohio State University television image system provides an overall contrast factor of the order of 5 to 10 without special amplifiers. A contrast amplifier has also been developed that can multiply these values by additional factors of 5 to 10, if desired. Few cases have yet been found where this additional contrast amplification was required, in industrial inspection.

It is also true that image contrast appears to diminish when images are enlarged to 30 diameters. When high-contrast film radiographs are examined under 30-power magnification, the apparent contrast is much diminished, and film grain often interferes with interpretation or visualization of details. The television image system, which involves no grain in its input sensing target, shows high detail and excellent contrast, with its normal 30-diameter enlargements, and is quite acceptable in contrast and detail with 60-diameter enlargements.

Penetrameter Sensitivities Attainable

The Ohio State University television image system was specifically designed for X-ray inspection of missile case materials and weldments of 0.1 inch thickness or thinner gages. Its optimum performance is consequently attained in this range, with in-motion inspection. Image quality indicators, or penetrameters, are difficult to procure or manufacture for thicknesses corresponding to two per cent of material thickness in this range. However, penetrameter tests have been made on steel and 2219 aluminum alloy specimens in the range from 1/8 inch of material thickness upward, for which Mil-271 type penetrameters could be procured. When the 1-T hole is visible in a two per cent penetrameter of this type, it is certain that two per cent penetrameter sensitivity has been attained. In some cases, visibility of the 1-T hole is now taken to represent 1.4 per cent penetrameter sensitivity.

With steel and similar materials, the Ohio State University X-ray television image system has permitted visualization of the 1-T hole in two per cent penetrameters, through 1/4 inch of steel or one inch of aluminum alloy, during in-motion inspection. With integration or scan-converter modification of images of stationary objects, these limits for visualization of the 1-T hole in two per cent penetrameters have been raised to 1/2 inch of steel, and to 3 inches of 2219 aluminum alloy.

With very thin gages of steel and lower-density materials, the apparent contrast sensitivity far exceeds that attained with the thicker specimens. However, no precision methods of evaluation, comparable to penetrameter tests, have been devised for this thickness range. Also, aluminum alloy spotweld images have been produced that are comparable to those attained previously with low-voltage, beryllium-window X-ray sources where the radiography was considered to be of the order of 0.2 per cent contrast sensitivity.

Tests made with the German DIN penetrameters (wires of various materials and sizes) have shown comparable performance, with the penetrameters located on the source side of the test materials.

Reproducibility of Performance

For practical applications in industry, an X-ray inspection system must be capable of reproducible performance, in order that inspection standards can be established and enforced. During the past half century, controls have been established for manufacture, exposure, and processing of X-ray films to provide a degree of reproducibility adequate for industrial requirements. In the case of the television X-ray image system, numerous factors can be left to the discretion of the operator, including: (a) X-ray kilovoltage, beam current, target size, and exposure geometry, (b) vidicon camera tube target voltage, black level and contrast controls, kinescope controls, and other television adjustments, (c) rate of motion and nature of scanning of test objects, (d) selection of positive or negative output images, and other factors. Continuous adjustment of variables can permit the operator to select optimum conditions for each inspection problem. However, failure to attain optimum conditions for each controlling variable could lead to loss of sensitivity and reliability in the inspection system, just as in the case of film radiography. Similarly, failure to maintain the electronic equipment in the television chain could also lead to deterioration of system performance.

It has been shown to be feasible to use punch-card control of the television system variables to permit reproduction of prior settings. If identical test objects were to be examined, at the same X-ray exposure conditions, this permits easy reproduction of prior operating conditions. Where a single inspection task involved objects with varying material thicknesses, such a control system can save considerable time for readjustment for different test object areas. Alternative systems can include use of panel meters for major control variables, or of a standard type of monitor to examine the waveforms associated with image scanning (a technique used in the broadcast elevision field). With transistorized circuitry, variations in component characteristics may be less of a problem than with systems using electron tubes. To date, all equipment in the Ohio State University system has performed excellently, with normal preventive maintenance procedures standard in the broadcast industry.

To date, the greatest variations in system performance and sensitivity have been a consequence of variations within the vidicon camera tubes, rather than in other parts of the overall system. Such tubes, now commercially available, must still be considered as experimental, and replacement vidicon tubes can be expected to vary in performance from tubes previously used. Operating control settings may have to be varied from those in prior use, when vidicon tubes are replaced. Vidicon tube manufacture is still an art, and even with light-sensing vidicons which have been produced for more than ten years, less than half of the tubes manufactured can be accepted for industrial or broadcast use. Major difficulties in both light-sensing and X-ray sensing tubes result from minute artifacts in target layers which can produce distinctive spots in the output images. Such spots offer more of a problem in X-ray vidicons than in light-sensing tubes, where signal levels are much higher and the spots can often be made invisible in output images. Experience indicates that such spots never tend to heal themselves in service, but normally grow in size and number as service life continues. Thus, limits are placed upon the location, size, and number of spots permissible in new vidicon tubes.

It is of interest that the first vidicon tubes manufactured to project specifications nearly three years ago, still perform perfectly and have actually improved in characteristics with increasing time in service. Other experimental models have been poor from the date of assembly, or have failed in a few weeks after initial tests. Failure in some cases appears to be a conversion of the target layer from an amorphous material to an insensitive crystalline form, a conversion that occurs spontaneously at a temperature of about 139 degrees Fahrenheit for selenium, for example. Thus, X-ray-sensing vidicon camera tubes should never be subjected to excessive temperatures in operation or in storage, for this type of failure appears to be a time-temperature phenomenon.

APPLICATIONS OF X-RAY IMAGE SYSTEM

Three broad areas of potential application appear promising for the television X-ray image enlargement system: (1) Inspection of critical aerospace materials, components, weldments, and assemblies, (2) Observation and control of welding and other critical processes, and (3) Use in scientific research and development.

X-Ray Inspection Applications

Immediate application of the television X-ray image system is taking place in aerospace industries for inspection of thin-gage missile case materials, weldments, brazed joints, electronic components, printed circuit assemblies, and other small-scale inspection operations. Studies are under way related to use of such systems for large-scale inspection of missile cases in increasing wall thicknesses.

Fusion Weldments. The television X-ray image system has been proven effective as a low-cost, high-speed, high resolution system for inspection of aerospace weldments, particularly in thin gage materials. In electron-beam weldments in sheet materials, it has revealed unsuspected porosity accumulation along fusion sidewalls. This porosity, often with pore sizes smaller than 1/1000 inch in diameter, tends to lie in one plane along each wall of the fusion zone. In tungsten inert-gas (TIG) weldments, the enlarged images of tungsten inclusions show that often many fine inclusions (again, often smaller than 1/1000 inch in size) can accompany the larger types of inclusions previously seen in film radiographs. Weldments produced by several forms of metal inert-gas (MIG) and carbon-dioxide gas shielded metal arcs, particularly with automatic welding equipment, have been successfully inspected with the television system. Unusual sensitivity to transverse and longitudinal crack networks has been attained. Relative motion of test object and source, with television X-ray observation, has shown that many cracks revealed on film radiographs were actually much longer (often 3 to 5 times longer) than the film images indicated. The gross portions of the cracks continue in many cases into a fine network of subsurface cracks, some of which are visible only at certain narrow angles of incidence of the X-ray beam. Thus, it is evident that weld repairs, based upon gouging out and repair of crack areas revealed by film radiography, may often be inadequate since the crack extends far beyond the limits of the repair. In still other cases, extremely fine cracks have been found to extend from small random porosity indications, being subsurface entirely. Since random small porosity is sometimes acceptable for certain types of service, whereas all cracks are rejectable, misleading interpretations can be based upon film radiography alone.

To date, all fusion weldment discontinuities detectable by film radiography have been readily detectable by the television X-ray image system, in material thicknesses within its range of application. In many such cases, additional discontinuities, not detected by film radiography, have been detected quickly in the enlarged television images. In fusion arc weldments, cracks, shrinkage networks, porosity, slag inclusions, undercut, lack of fusion at sidewall and at the root of the weld, tear-drops or drip-through, suck up or concavity at the root, and numerous other discontinuities have been observed. In fusion spotwelds in aluminum alloys with copper or zinc alloying elements, it has been possible to detect the dark ring outlining the nugget area at the interface, segregations of copper-rich eutectic, cracks, porosity, shrinkage defects, expulsion, and similar defects that X-rays can reveal.

Weldments in miniature electronic components, fine wires, and sheets have also been examined with the television system. Electron tube assembly, transistor details, connections to leads of components such as resistors, capacitors, inductors, and transformers, and other components often only a few thousandths of an inch in diameter have been inspected.

With the scan converter system, faint indications of weld defects seen by in-motion inspection have been intensified and made clearly visible. This integration system now extends the capabilities for weld inspection to about 1/2 inch of steel and to about 3 inches of aluminum alloys.

Brazed and Soldered Joints. The television image enlargement system also provides unique detail sensitivity for inspection of brazed and soldered joints, particularly in thin gage and small parts. In inspection of brazed stainless steel sandwich and honeycomb structures, the internal details of braze alloy voids and porosity, or loss of filleting or node flow, appear reamrkably clearly in the enlarged images. With honeycomb core wall only 1.5 mils in thickness, the individual fillets on either side of the core wall can be seen separately. Node flow, and in some cases even the depressions caused by welding the node flats together, can be seen. Lack of filleting, intermittent filleting (even for 1/100 inch of length), cell repairs, cell wall perforations, crushed or distorted cells, and many other conditions are visible. In sandwich materials, or in edge members or close-outs of honeycomb panels, the distribution of braze alloy at the interface can be examined in detail. Often porosity of minute dimensions is found in the interfacial areas. Similar observations can be made of brazed joints in thin-walled tubes and other brazed assemblies.

Of particular interest for aerospace electronic applications is the use of the television system to inspect miniaturized electronic components and printed circuit assemblies. With dip or hand soldered joints, it is often found that extensive porosity exists in the solder at terminals, or that terminals have been inadequately filled with solder to hold the leads. In many cases, it has been observed that thin, transparent (to X-rays) films surround wires in soldered joints (observable only when the X-ray beam is exactly aligned with the sidewall of the soldered wire or part). These cases have been interpreted as indicative of cold-soldered joints. Other cases have been observed where a film of solder covers a broken lead wire, or where wire "whiskers" smaller than a mil in diameter extend partially or completely between printed circuit conductors.

Foils, Sheet, and Plate. Limited observations have been made on thin gage sheet and foils, and on steel and aluminum alloy plates of 1/20 to 1/2 inch in thickness. In several cases, striations in the direction of rolling are clearly revealed. Steel specimens, with fine cracks initiated by nascent hydrogen and stress, have been examined and all known cracks detected, including some so fine that film radiography had generally failed to detect them. Some of these specimens also contained unexplained mottling as if films of non-metallic materials had been elongated by rolling. Weld cracks that extend outward into base material have also been seen in many specimens.

Small Castings. Small castings of magnesium, aluminum, and dense alloys have been inspected by the television system. In light alloy magnesium castings, individual grain structure was revealed, together with other discontinuities. In turbine blade alloys, structure is much more clearly evident, and often interferes with interpretation of the X-ray images. Small protrusions into internal cooling passages of blades could be seen clearly in precision investment castings. In some cases, observers thought they had detected the transient appearance of diffraction lines from coarse-grained castings (lines that moved many times faster than the images of structure).

Graphite and Non-Metallic Materials. Extensive striations and other artifacts were visible in enlarged images of graphite specimens. Also visible were inclusions of denser materials, and apparent low-density areas, in some specimens. Fiber glass laminates have been examined extensively. With only a few layers, the individual strands or rovings often appear clearly, and the direction, lay, or density of fiber packing can be seen. With complete missile case walls, including liner materials, useful images were obtained that showed the principle fiber directions, void or low density areas, inclusions of dense materials, and other defects.

Small Mechanisms. Small mechanical devices such as watches, fuses, relays, valves, and others can be examined readily, even in motion, with the X-ray image system. Movements of parts can be observed, and spacings or clearances measured to an accuracy of the order of 1/000 inch, from the enlarged images of hermetically-sealed assemblies. In one case, the movement of oil in a watch bearing could be seen clearly as the shaft rotated.

Wires, Tubes, and Small Rods. Elongated objects such as wires, cables, coated welding rods, thin-walled tubes, range heater coils, and others are particularly well suited for inspection by means of the X-ray television system. If not more than 1/2 inch in diameter, they can be scanned longitudinally, often while rotating in the fixture. This permits many views, so that eccentricity of coatings or internal structures, and other irregularities can be seen from many angles. Longitudinal and transverse welds in tubes can be seen in many cases, even with tubes filled with other materials. Movements of fluids in tubes, or of bubbles in fluids, can be seen through the tube walls in some instances.

Observation and Control of Welding Processes

Possibly of greater potential importance than post-mortem inspection applications is the use of the television image system to observe and control welding and brazing processes. To the extent that the formation of discontinuities or loss of control of welding processes can be observed during operation, and corrective measures applied, the number of rejectable conditions in finished weldments can possibly be greatly reduced. This can reduce the great costs of gouging out and repairing weldments (in structures that can be repaired), and may become essential in production of weldments that cannot later be repaired.

Preliminary studies have been made to determine the feasibility of direct X-ray observation and control of metal inert-gas (MIG) welding of 3/8-inch 2219 aluminum alloy sheets. Three major problem areas were encountered: (1) requirements for thermal shielding of the television camera from the heat of the welding arc and the molten and base metals, (2) modification of welding fixtures and equipment to permit introduction of the X-ray source and television camera unit at the point of welding, and (3) provision of X-ray shielding to protect the operator and environment from ionizing radiation exposures. Solution of these problems permitted direct observation of the X-ray images of (a) metal transfer, (b) the molten weld pool, and (c) the solidifying weld metal, according to the position of the camera unit along the line of welding. With the primitive initial set-up, images were not as clear as those obtined in weld inspection of finished welds, but the drops of metal transferring, the movements and escape of gas porosity bubbles from the melt, penetration of fusion to the root of the weld, and the formation of cracks in the solidifying weld metal were all seen clearly. Several new observations, such as the trapping of inclusions in the molten pool for long periods of time, crack growth in successive stages, and the dynamics of escape of gases from the melt, were of particular interest. Further studies are planned in the near future of submerged arc welding phenomena.

Considerable interest has been aroused by the possibilities of controlling welding processes directly by three-dimensional X-ray examination of the molten pool and adjacent areas. Such techniques could be applied to control of aerospace welding, particularly of large missile cases, if means could be found to introduce the X-ray source and television camera at the point of welding. An alternative procedure would be to insert the inspection system a few inches or feet down the weld line from the point of welding. If trends toward defects such as lack of fusion at the root, sideway drift of the arc tending to produce lack of fusion at a sidewall, trapping of porosity in the deposited metal, cracking during solidification or cooling, undercut or overlap, and others could be detected during welding, the process could be adjusted to avoid weld defects in the finished welds, or interrupted until corrections could be made. Potential cost, material, and time savings from such a development could be of great value to the aerospace industry. Rapid feed-back of X-ray inspection information is the basis of such controls.

Use in Scientific Research and Development

The television X-ray image system, like the light microscope and other instruments, can be used as an observation and measurement tool in many kinds of basic research, as well as in engineering development. Obviously, it could be of direct assistance in evaluation of new welding processes, materials, and procedures. X-ray examination of the process as operating conditions were varied could provide almost instantaneous information on the effects of welding variables. In many cases, the causes of weld defects might be identified. Studies of braze alloy flow and bonding might also be greatly expedited if tests were made while enlarged X-ray images were being observed. Of particular interest is the possibility of observing the propagation of defects and failures in materials with capabilities for plastic deformation before failure, during mechanical destructive testing. With electron beam welding, for example, the X-rays generated by the electron beams themselves, upon absorption in the work material, might possibly serve as radiation sources internal to the melt, from which the point of impact, and the internal conditions, might be deduced.

Other possible research applications might include studies of the flow of metal in precision investment casting, of the successive deformation of inclusions or porosity during rolling or forging, and of the attack of corrosive fluids upon specimens at various temperatures. Still other possibilities include observation of enclosed structures and mechanisms during loading or operation, to determine stress distributions or deformations. Fluid flow problems might in some cases be expedited by studies of this type. And finally, biological studies on small animals, insects, and similar small forms of life might be made both in the laboratory and in outer space, to determine responses to various stimuli and environments.

ACKNOWLEDGEMENTS

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Fig. 2 X-ray television system equipment racks, X-ray control, and operating console for X-ray imaging research.

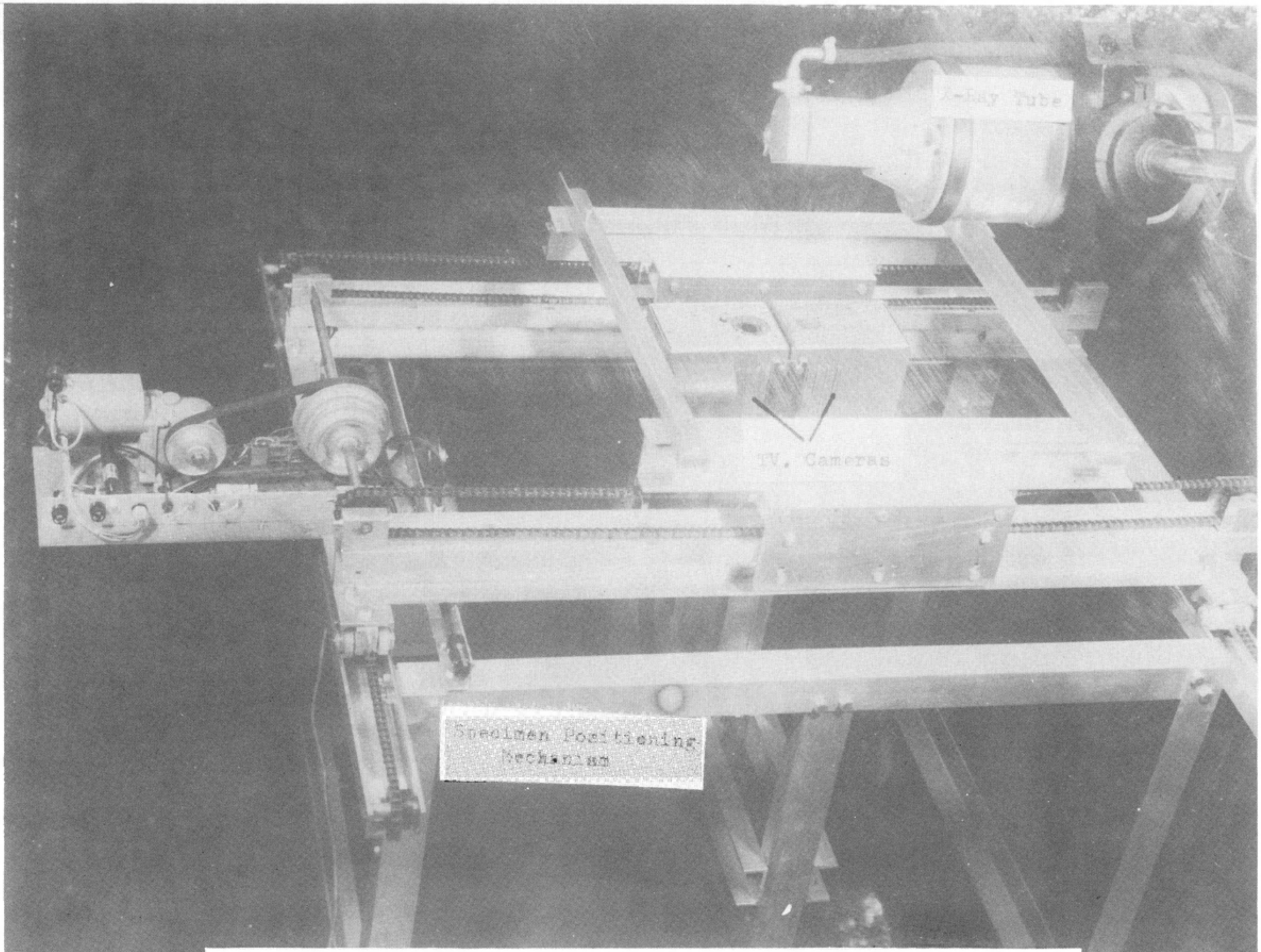

Fig. 3 Arrangement of X-ray source, television cameras, and specimen positioning mechanism for X-ray imaging inspection.

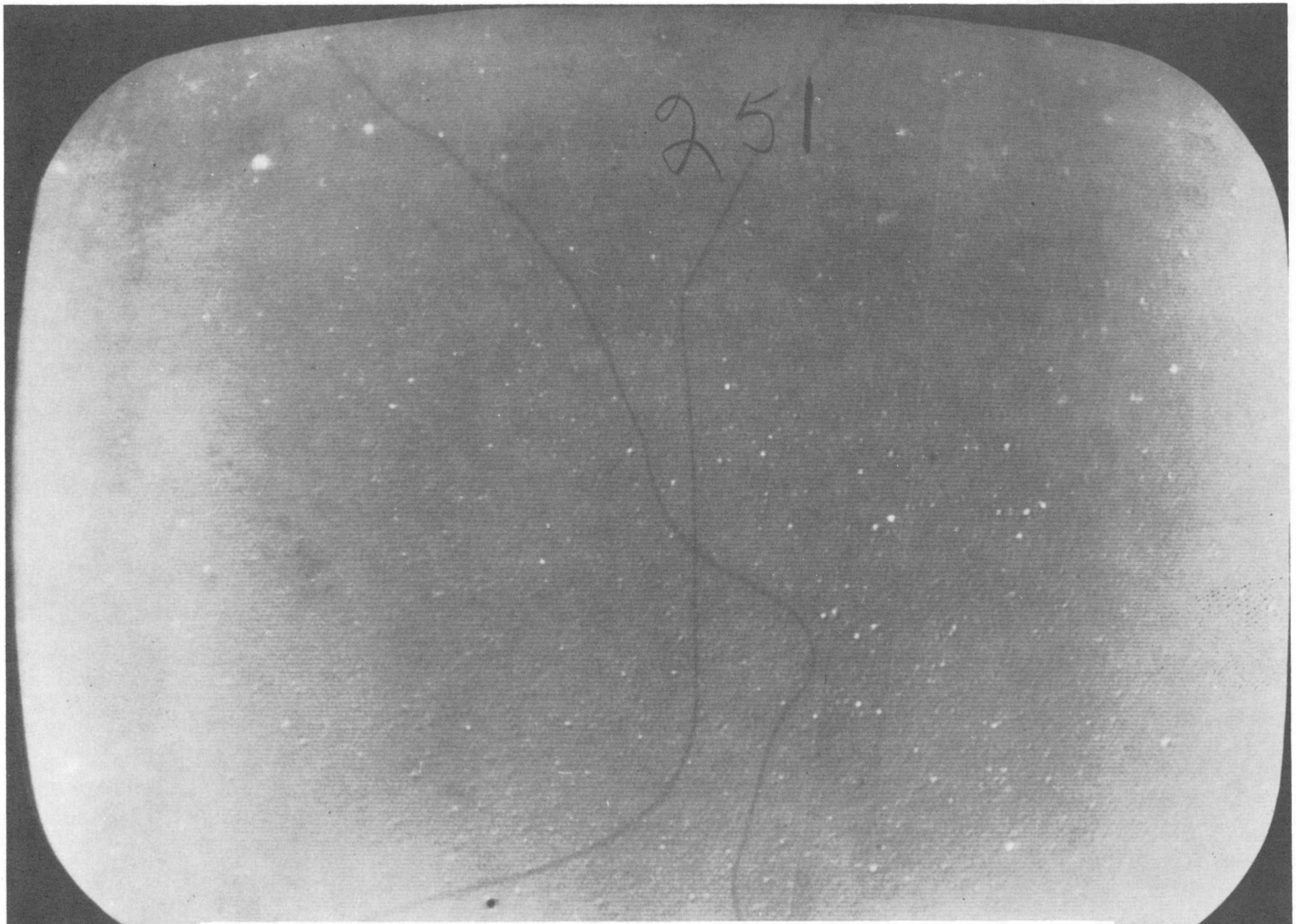

Fig. 5a. Resolution of 10-micron (390 microinch) diameter wires by Ohio State University television X-ray image enlargement system. 30X

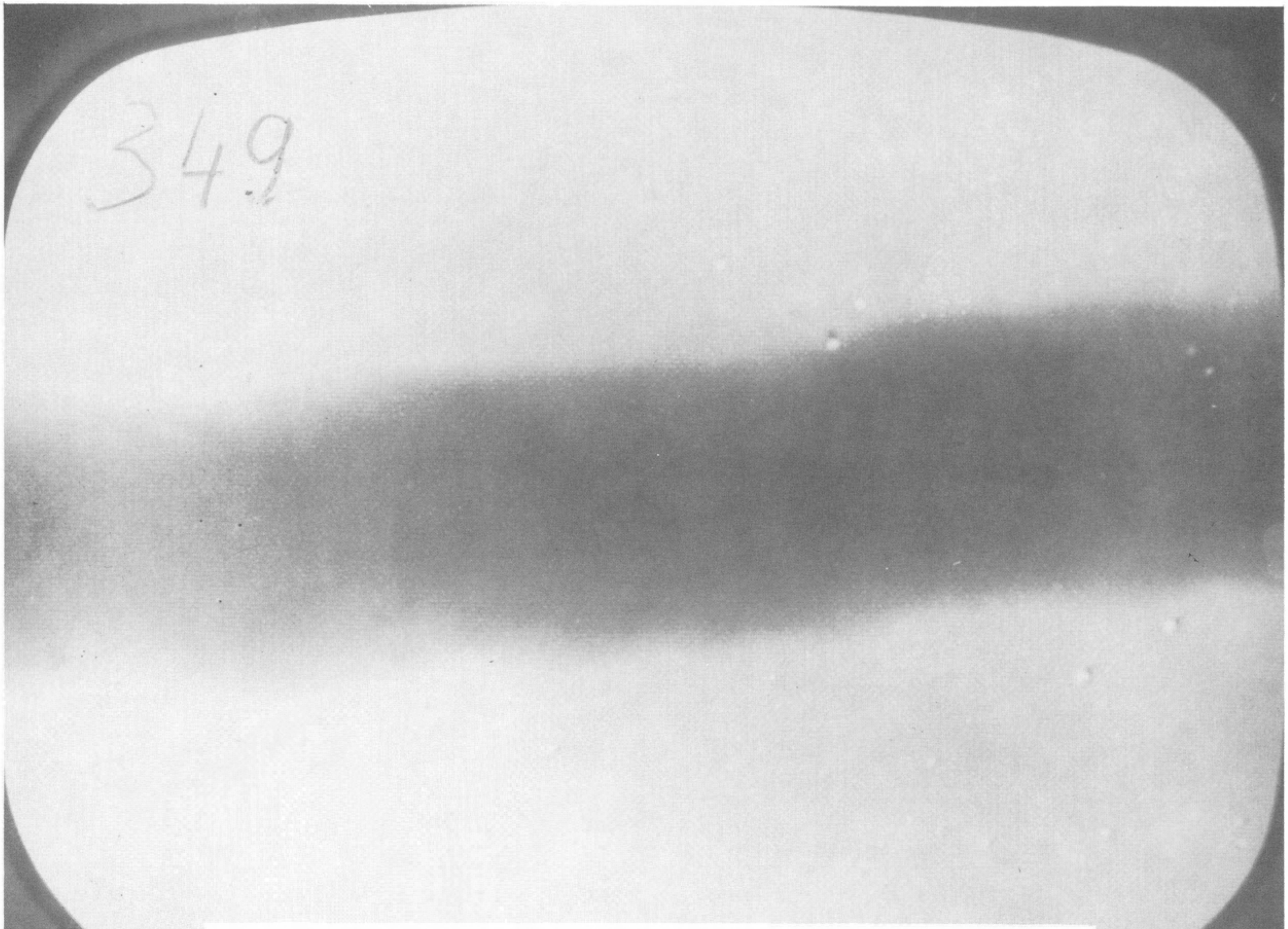

Fig. 7 Television X-ray image of good fusion weldment in 0.050-inch aluminum alloy. The Ohio State University X-Ray Image System.

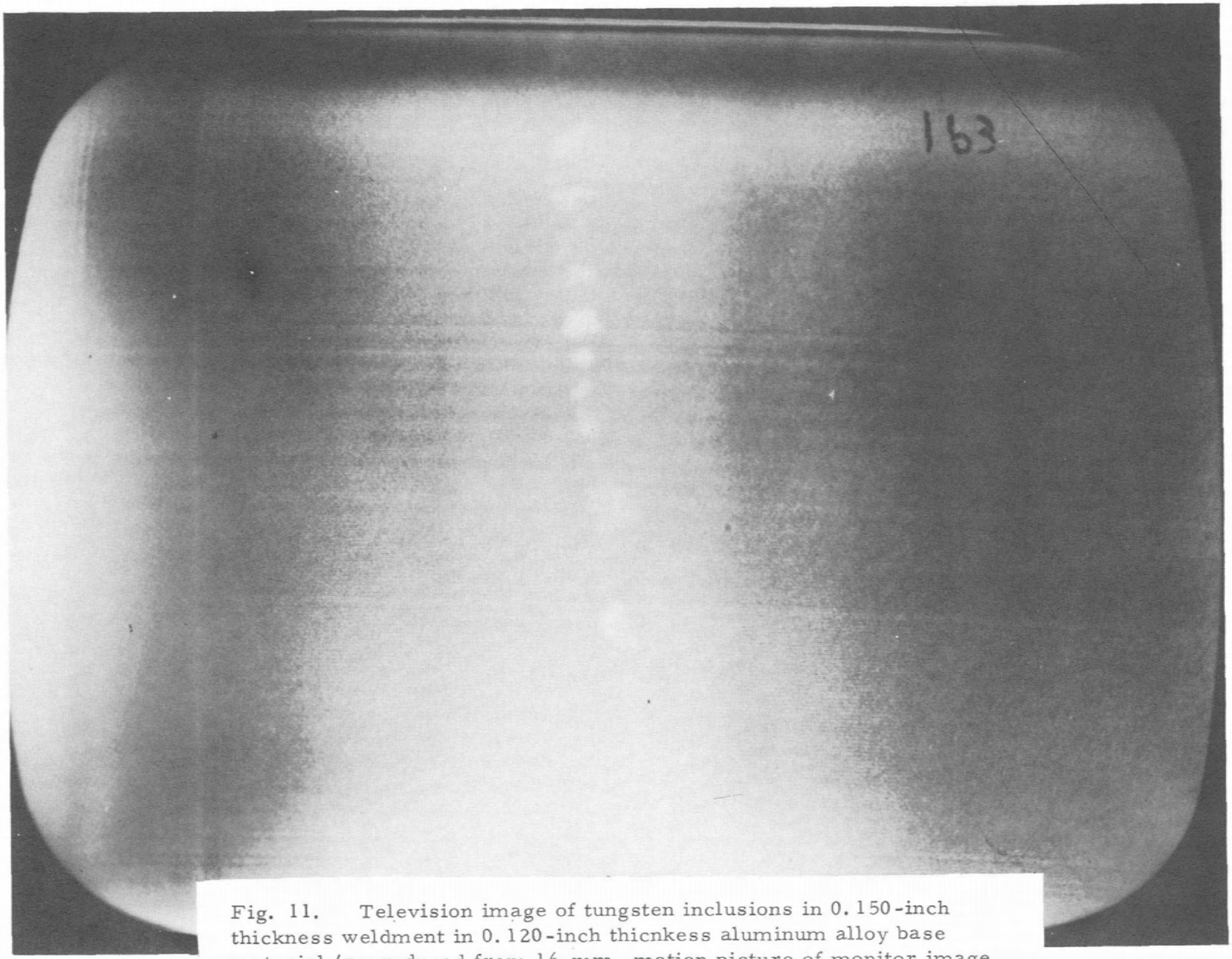

Fig. 11. Television image of tungsten inclusions in 0.150-inch thickness weldment in 0.120-inch thicnkess aluminum alloy base material (reproduced from 16-mm. motion picture of monitor image of moving specimen). Ohio State University X-Ray Image System.

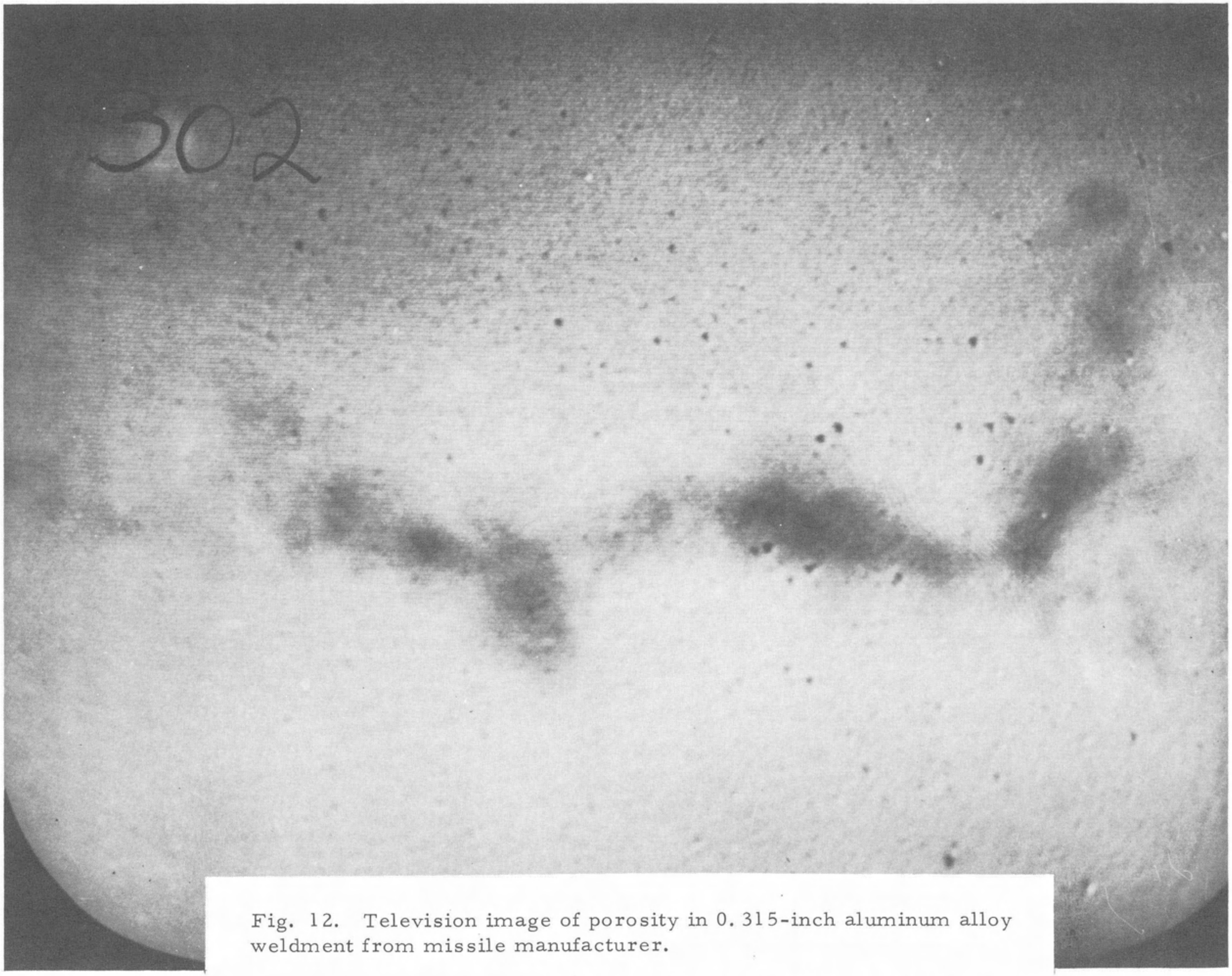

Fig. 12. Television image of porosity in 0.315-inch aluminum alloy weldment from missile manufacturer.

Ohio State University X-Ray Image System.

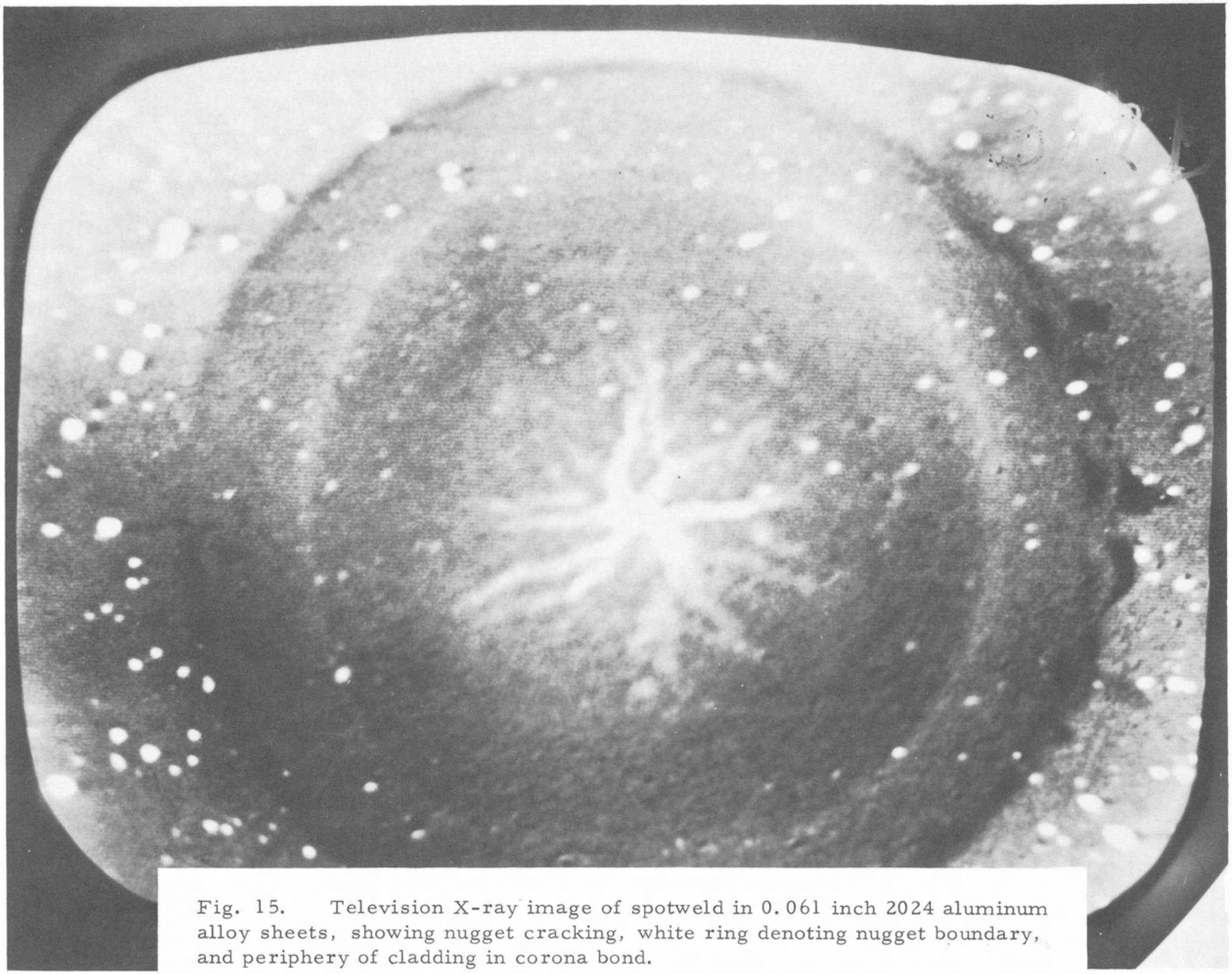

Fig. 15. Television X-ray image of spotweld in 0.061 inch 2024 aluminum alloy sheets, showing nugget cracking, white ring denoting nugget boundary, and periphery of cladding in corona bond.

Ohio State University X-Ray Image System.

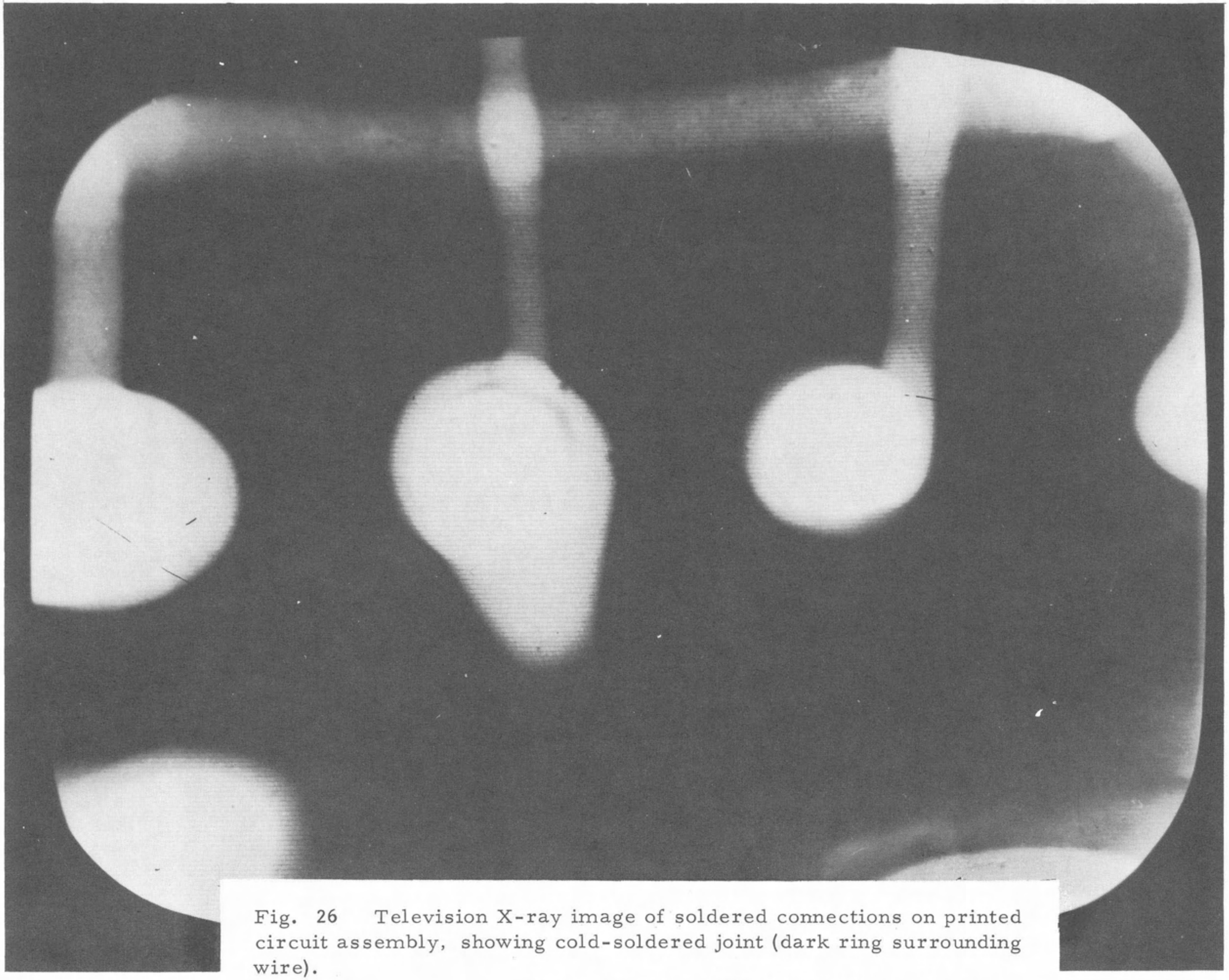

Fig. 26 Television X-ray image of soldered connections on printed circuit assembly, showing cold-soldered joint (dark ring surrounding wire).

Ohio State University X-Ray Image System.