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THE APPLICATION OF IMAGE ENHANCEMENT TO FFTF FUEL TECHNOLOGY

B. R. Hayward

May 1970

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APPLICATION OF IMAGE ENHANCEMENT TO FFTF FUEL TECHNOLOGY

B. R. Hayward

ABSTRACT

Current technical data analysis and evaluation methods are reviewed. Image enhancement is one of the advanced methods which is in the preliminary stages of application to nuclear technology. Interest in these systems lies in the extraction of more data from standard negatives than is presently obtained. Application of these techniques to earth sciences, medicine, and space technology has already been demonstrated. Typical types of application to fuel work include X-rays, neutronradiographs, autoradiographs, electron diffraction patterns, and photomicrographs.

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THE APPLICATION OF IMAGE ENHANCEMENT TO FFTF FUEL TECHNOLOGY

INTRODUCTION

A prominent product from space age technology is the tremendous growth in data handling methods. Current communications methods in use and in development are rapidly outgrowing fairly conventional equipment, including the human eye. Technical data analysis and evaluation, as well as data handling, are undergoing rapid improvement. Many of these techniques have been developed for use in the fields of electronics, medicine, and military intelligence. However, relatively minor application of this information, such as image enhancement, has been introduced into the nuclear materials area.

A recent industrial journal article brought the status of data processing technology into focus.[(1)] This growth of computer software development is illustrated in Figure 1. The first generation programs started in about 1953 and have grown through three five-year periods to the modern programming language. The computer software evolution is toward programs that provide both wide-range capability and analytical depth. Further growth in this area includes video graphics which permit the manipulation and simultaneous display of data.

There are three methods of image enhancement in the preliminary stage of investigation by Battelle-Northwest in the Fast Flux Test Facility Program (FFTF): (1) photographic, (2) optical, and (3) computer.

The interest in image enhancement, or data expansion, lies in the firm evidence that substantial additional data can be extracted from ordinary photographic negatives. Many technical programs covering a multitude of scientific disciplines use photography as a means of recording data. More advanced

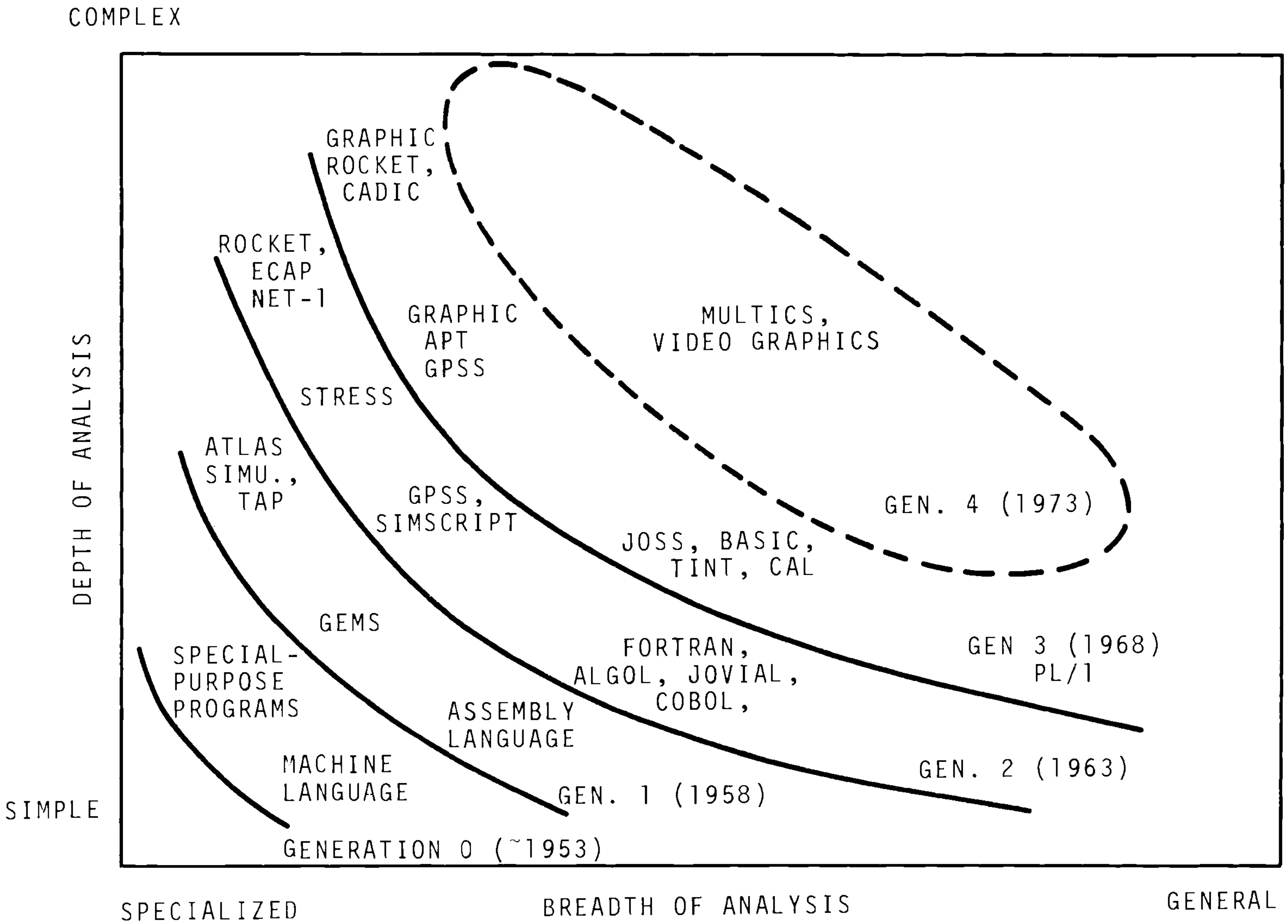

FIGURE 1. COMPUTER SOFTWARE GROWTH

techniques, as you will note, will bypass the photograph and transmit, record, store, and analyze the data directly from the sophisticated sensor such as the electron microscope and produce the enhanced negative as a final product. The image enhancement processes attempt to expand the data that are normally observed, by processes such as edge sharpening and filtering unnecessary matrix material on the negative.

On the basis of a cursory examination of the current scientific literature, it is literally astounding to find at random the high level of effort being placed on image processing. The articles and papers reflect a very high degree of rapidly advancing sophisticated technology, both in theory and practice. Entire companies and substantial divisions in some large corporations are devoting their efforts to this technology.* Annual conferences, such as those sponsored by the Society of Photo-Optical Instrumentation Engineers, were innovated in the period 1965 through 1968.[2] Considerable equipment is available on the open market that performs various aspects of image enhancement. Consoles for volume processing are available. In August 1969 a short course in image processing was taught at UCLA. Most recently, highly publicized examples of image processing and enhancement were obtained from the Mariner, Ranger, and Apollo 11 space programs.

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* Typical groups participating include: Technical Operations, Inc.; International Business Machines; Itek Corp.; Conductron; Eastman Kodak; Philco Ford; Xerox; General Electric; Information International; National Bureau of Standards; Cornell Aeronautical Laboratory; Jet Propulsion Laboratory; M.I.T.; Scripps Institute; North American Rockwell; Aerial Reconnaissance Laboratory; Wright Air Development Center; University of Michigan; Information Technology Corporation; Dicomed Corporation; Spatial Data Systems, Inc.; International Imaging Systems.

SUMMARY AND CONCLUSIONS

- Image enhancement is one of the major advances made in data processing methods by the space and defense industries. It provides new methods to extract more data from a photographic negative. As a result of image enhancement, the ordinary photographic negative can be considered only an intermediate step in obtaining the desired information.

- Three methods of image enhancement, photographic, optical and computer, are currently available techniques applicable to many disciplines including medicine, agriculture, military intelligence, geology, art, and education. Although they have received only cursory evaluation of their applicability to the nuclear industry, photographic image enhancement is now being used very successfully for the examination of neutronradiographs of irradiated fuel pins at EBR-II. Other potential FFTF uses include X-rays for NDT, autoradiographs, electron diffraction patterns, and metallography. These processes have a large potential for increasing the quality and quantity of data for a minimal incremental cost.

- All data processing that uses photography should investigate these new techniques in order to optimize the results obtained. Coordination between the test initiator and the enhancement analyst is required. Reference standards are recommended.

- The application of these new data processing methods should be vigorously pursued. Support of development in this area will increase the amount and quality of information obtained from R&D programs.

EXAMPLES OF IMAGE ENHANCEMENT

PHOTOGRAPHIC

Introduction

The representative examples that demonstrate the capability of photographic image enhancement are from the space, medical, and nuclear materials technology fields. Excellent additional examples are available for review from other technical disciplines such as geology, agriculture, and marine fields. The use of this process for interim examination of irradiated fuel pins by neutronradiography for the LMFBR/FFTF program represents a major step forward in data interpretation techniques. An interim examination is a nondestructive examination performed at periodic intervals. The photographic method received the most emphasis primarily due to availability, cost, and application. During the course of data accumulation, it was evident that every negative was not going to reveal large amounts of new data. If the data are not on the negative, they cannot be extracted. It also became apparent that current practice in taking technical information grade pictures requires substantial care and preparation. Discussions, with the photographic engineers providing the photographic enhancement service,[3,4] indicated a general technology gap between researchers or development engineers and the photographer. Both the quality and quantity of data from a negative can be expanded by consideration of the following:

- Optimum paper type for the photographic conditions; e.g., small grain size for high resolution, speed.
- Correct exposure to include all data of interest; e.g., two or three separate exposures may be required (such as with X-rays or neutronradiographs that have different

penetrating power through different thickness or varying densities of materials).

- Photographic conditions that may cause, for example, reflected exposure of the film due to backup plates.
- Optimum choice of light or sensing source such as neutron flux intensity and colimation for neutronradiography.
- Density, composition, and dimensional standards to increase the accuracy of measurements and to directly relate to pre-post test results.

This last factor is the most important because such standards are absolutely necessary for nondestructive testing work.

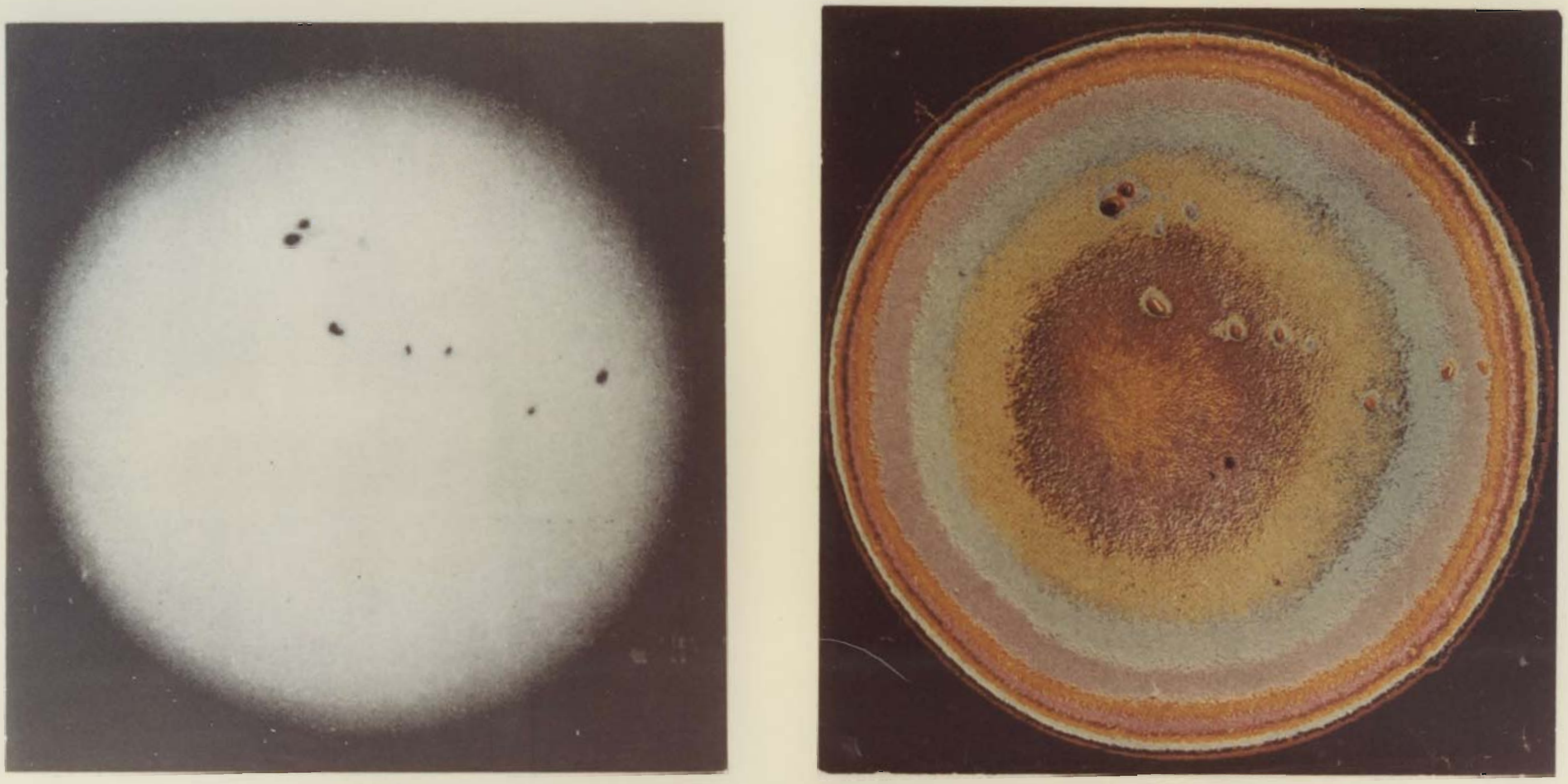
The capabilities of the photographic enhancement technique are shown in the seven examples provided. This enhancement method essentially separates by precision photography the gray tones or density levels that appear on a negative. A brief description of the process is given in the appendix.

Sunspots

One of the most dramatic examples of enhanced images is shown in the normal and color enhanced images of sunspots in Figure 2.[5] Don Ross of Philco Ford took a high quality black and white picture of the sun showing the fairly common sunspots. This negative was then image enhanced and reproduced in color by arbitrary assignment of colors to the gray tones or density slices. The enhanced image revealed major data additions such as more sunspots formerly either vague or unobserved, and a solar flare on the outer rim at about "five o'clock."

Skull

A second equally dramatic example of the capability of photographic image enhancement comes from the medical field.



NORMAL A

ENHANCED B

FIGURE 2. SUNSPOTS

A normal and enhanced color X-ray of a skull are shown in Figure 3. Among the special features to be observed in the enhanced photo are:

- The layers of outer tissue covering the skull
- The outline of the lips and part of the nose
- The small unknown "loop" on the outside rear of the head
- The nasal and sinus passages.

The same data are present in both photographs but the enhancement process makes much more data visible by elimination of photographic density levels that mask the key details. The arbitrarily assigned color tones further permit the eye to separate areas and edges that previously appeared to overlap and resulted in judgmental uncertainty. Since the color enhanced photo in Figure 3 is actually a composite, it is possible to examine even greater detail by looking at the individual transparencies. During the interpretation of this type of enhancement it is recommended that copies of the original negative be placed side by side with the enhanced results to clarify and confirm observed data.

The graph indicated on Figure 3 is the typical "characteristic" curve superimposed on this example to show the normal density range in the original and the colored "slices" taken out by this process to yield the color enhanced result.

Irradiated Stainless Steel

The decrease in density of stainless steel materials in a fast neutron flux environment is one of the main problem areas in the FFTF fuel technology program. Under certain conditions, which are not completely understood, voids form in the stainless steel and result in lower density. This phenomenon is being analyzed and evaluated in order to understand the mechanisms of void formation (holes). An original electron microscope picture of irradiated stainless steel is shown in black and white in Figure 4. This image was processed for image enhancement in black and white, and color. These results are shown in Figure 5.

As in the previous images of the sunspots and the skull, additional data were observed and confirmed that were not available in the original observation in Figure 4. Fourteen separate density slices were reduced to individual transparencies. Four of these are shown in Figures 5a, 5b, 5c, and 5d. A composite of four intermediate densities is shown in Figure 5e. The composite shows a stronger image than one narrow single density "slice." The most important observations are shown in 5c and 5e where two concentric oval shaped rings appear near the center of the image. It is believed these rings are related to dislocation loop formation, movement, and void formation. The significance of these rings is still being analyzed. The concentric ring phenomena are actually limited to a few density intervals near the center of the "characteristic curve" and are not even suspected in the overall composite. In addition, the lineup of microstructural details was reinforced by the data in the enhanced image. This is another example that illustrates the need to compare the enhanced results with the original negative to best interpret the results.

Fuel Pin Neutronradiography

Driver fuel pins for the EBR-II fast reactor are made by casting a uranium alloy containing ∿5% of fission product elements. The pins are 0.155 in. diam and ∿13-1/2 in. long. The fuel pins are clad in thin-walled stainless steel tubes and contain a 0.006 in. sodium bond between the fuel and the clad. It is important that these pins meet stringent quality control specifications. Since fast reactor fuel performance

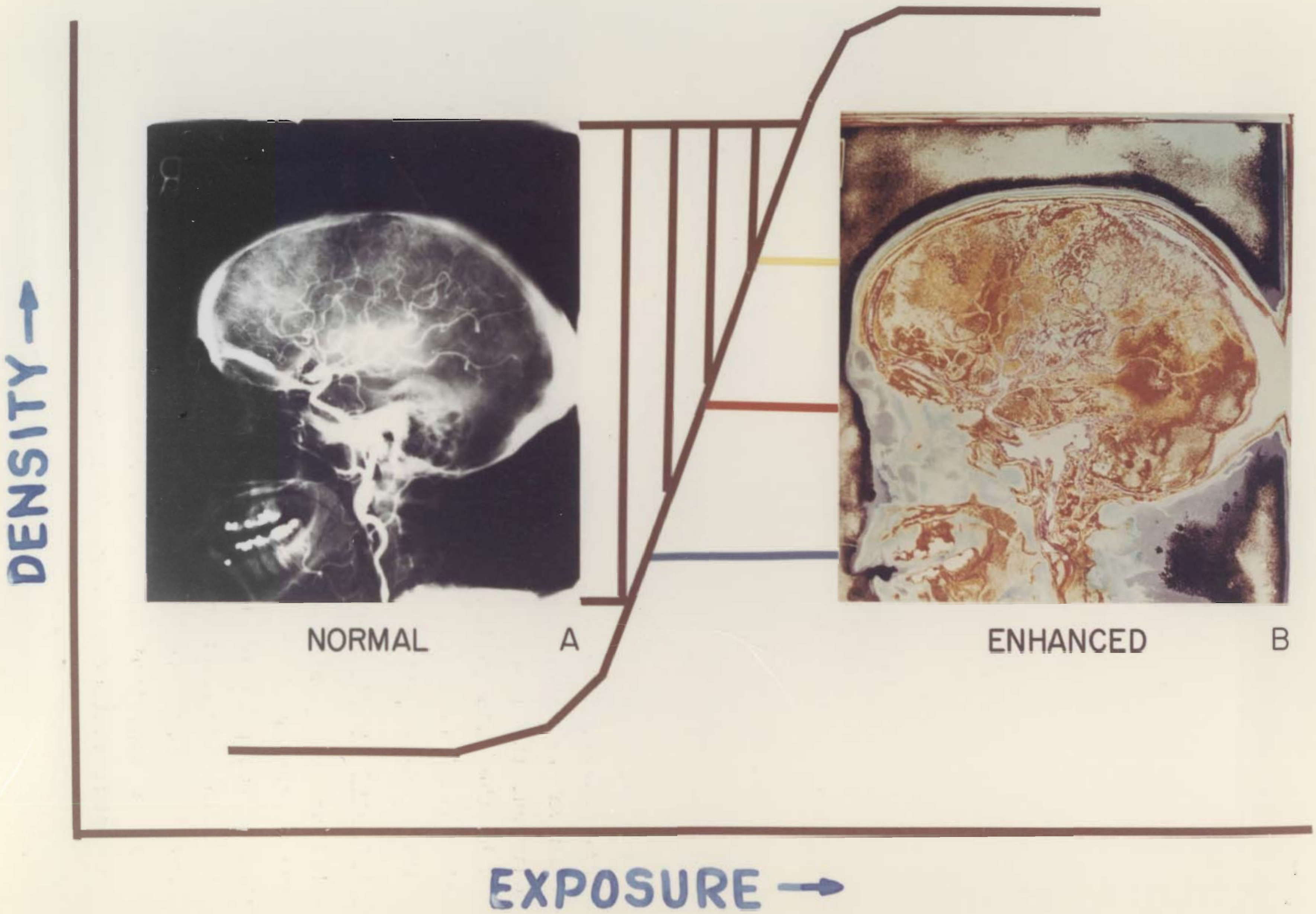
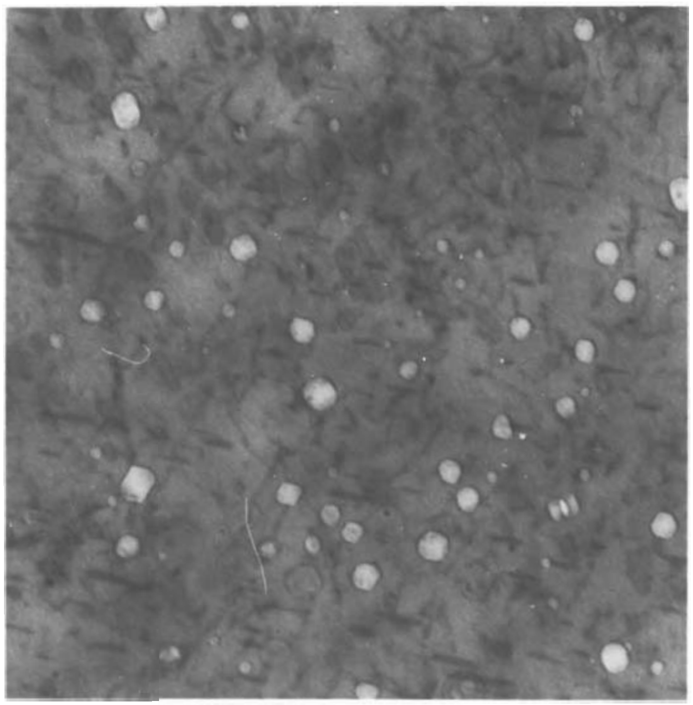
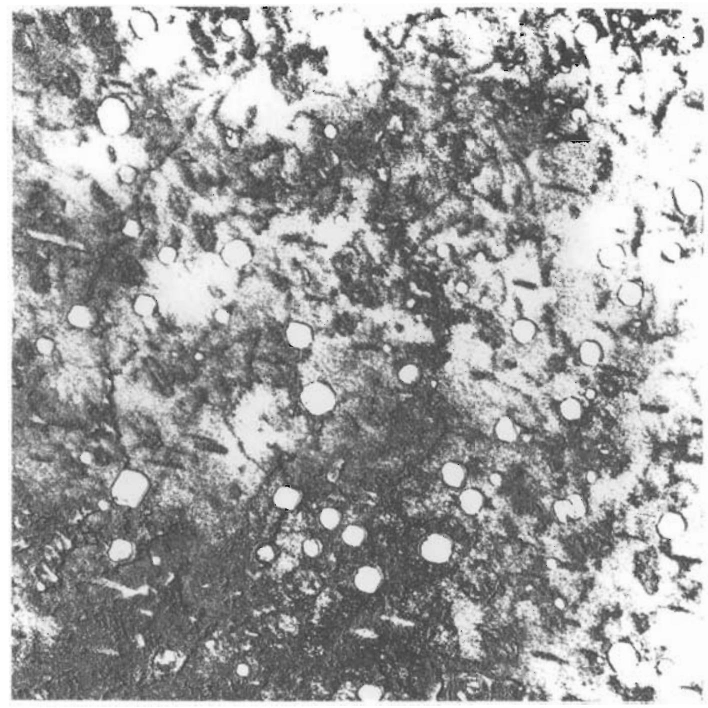


FIGURE 3. SKULL



NORMAL (4)

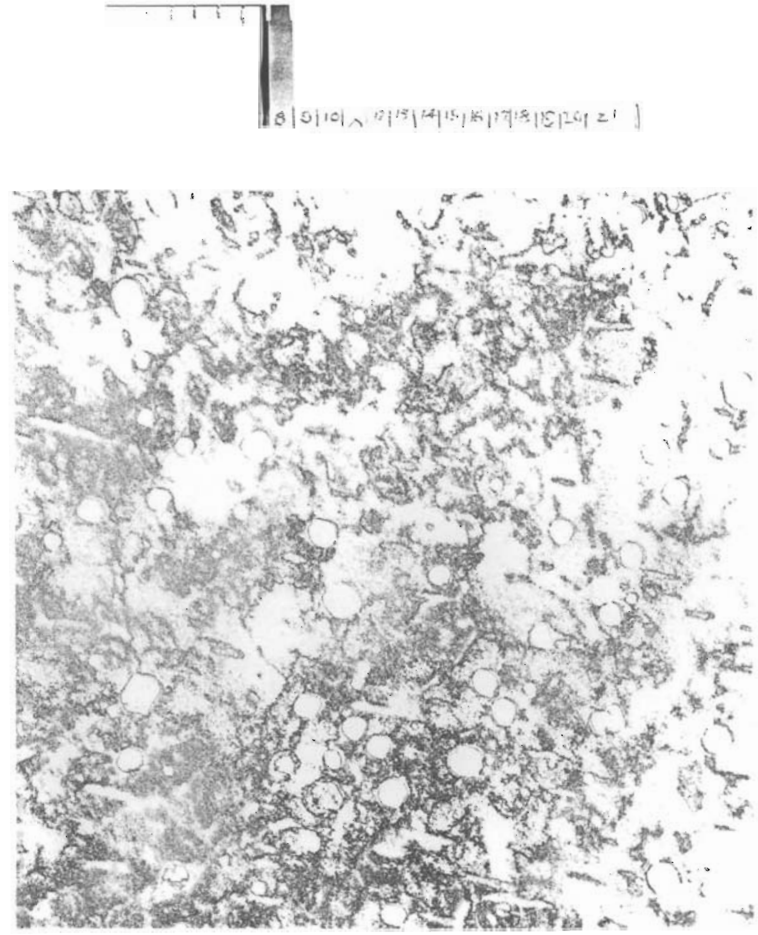


COMPOSITE (5e)

FIGURE 4. IRRADIATED STAINLESS STEEL

FIGURE 5. IRRADIATED STAINLESS STEEL

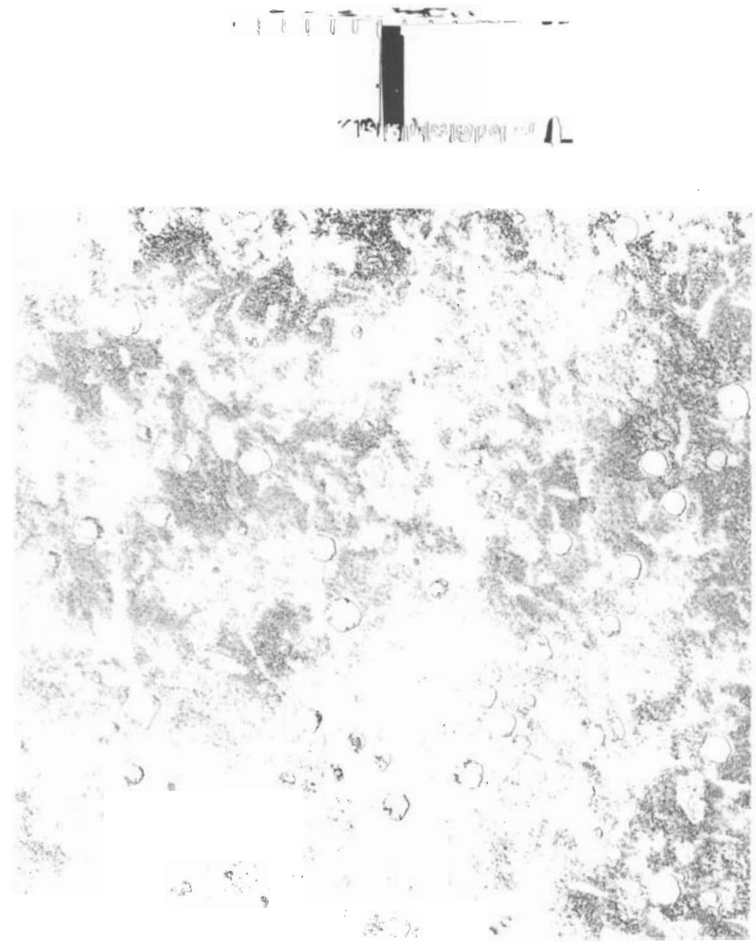
(5a)



(5b)

FIGURE 5. IRRADIATED STAINLESS STEEL

(5c)



(5d)

FIGURE 5. IRRADIATED STAINLESS STEEL

technology is new, data are still being collected, evaluated, and interpreted through preirradiation, interim, and post-irradiation examinations.

Four recent driver fuel pins were examined by neutronradiography at an interim exam and three pins showed a decrease in length as grossly indicated in the original negative in Figure 6a. The neutronradiograph was then photographically image enhanced by Lohse of Philco Ford to show internal fuel pin flaws. One gross flaw was indicated in the bottom pin on the unenhanced original neutronradiograph. Figure 6b shows the enhanced images with additional flaws. After eighteen separate photographic density intervals were produced, it was evident that numerous smaller flaws were present in the same rod and similar minor flaws are shown in the other two shortened pins. These flaws have been identified by destructive examination to be shrinkage cavities. Even though these flaws are not believed to be related to the fuel pin shortening process, these particular pins probably would have been rejected by the quality assurance program if they had been observed. The five density intervals of the same fuel pins are shown in Figures 7a, 7b, 7c, 7d, and 7e, and indicate density intervals from under- to overexposed conditions. The central print 7c (same as 6b) is the optimum density slice to reveal the flaws. Note that the print showing the most flaws does not show as much diameter detail as the other density intervals. The outside surface of the pins (diameter) is represented by another density level and does appear in other negatives in the series. The observer may use different density intervals or combinations of density intervals for other data, such as dimensions. It should be noted that the different photographic densities on the neutronradiograph are due to the difference in neutron cross section between the steel clad and the uranium fuel.

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Thus additional data may also be obtained by an original decision at the time of preparing the transparency to emphasize a special attribute for examination, or, perhaps two different exposures should be made at that time to include both attributes. Argonne National Laboratory at the EBR-II site is now successfully using this image enhancement process to measure precise EBR-II fuel pin diameter changes to 0.0005 in. This result is a major improvement in diameter measurements over previous techniques and it is completely nondestructive. Upon the addition of standards to the interim neutronradiograph, the diameter measurements may be reduced to <0.0005 in. EBR-II personnel have further confirmed these results by comparing EBR-II postirradiation pin diameter physical measurements with measurements estimated from the enhancement negatives. The 100% agreement verifies the importance and value of the enhancement results.

OPTICAL

Introduction

The optical enhancement examples shown are from the biology, ocean surveillance, and nuclear materials technology fields. The capability of this method is wide and its use depends on the specific application. In the two examples for nuclear materials, the photography used was regular Polaroid film, thus the resolution is less than optimum but the relative examples are well illustrated. The optical filters used were quite limited and concentrated on the edge-sharpening aspects of the process. The biological example is from a recent Scientific American article[6], thus, some of the details are unavailable; however, the example is excellent. The optical image enhancement investigations at Battelle-Northwest are very preliminary. Due to the BNW experience

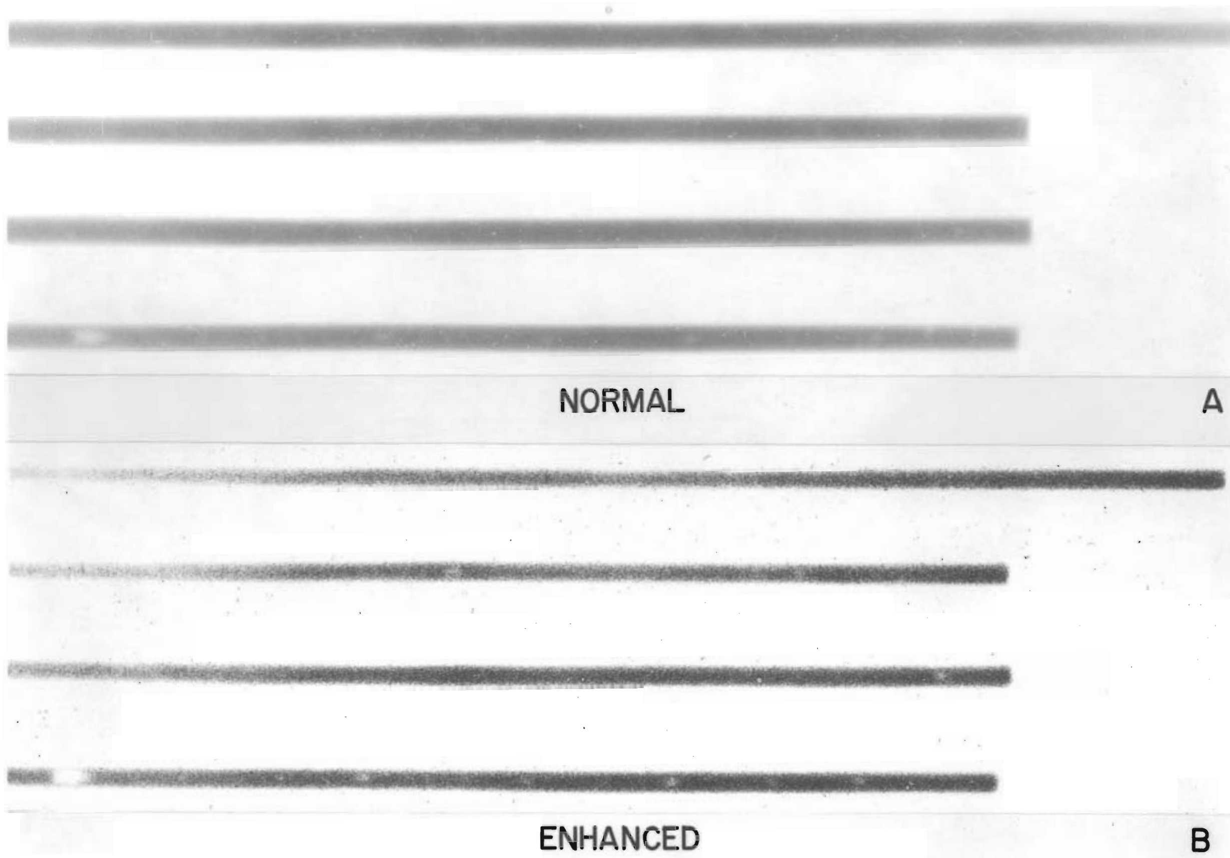
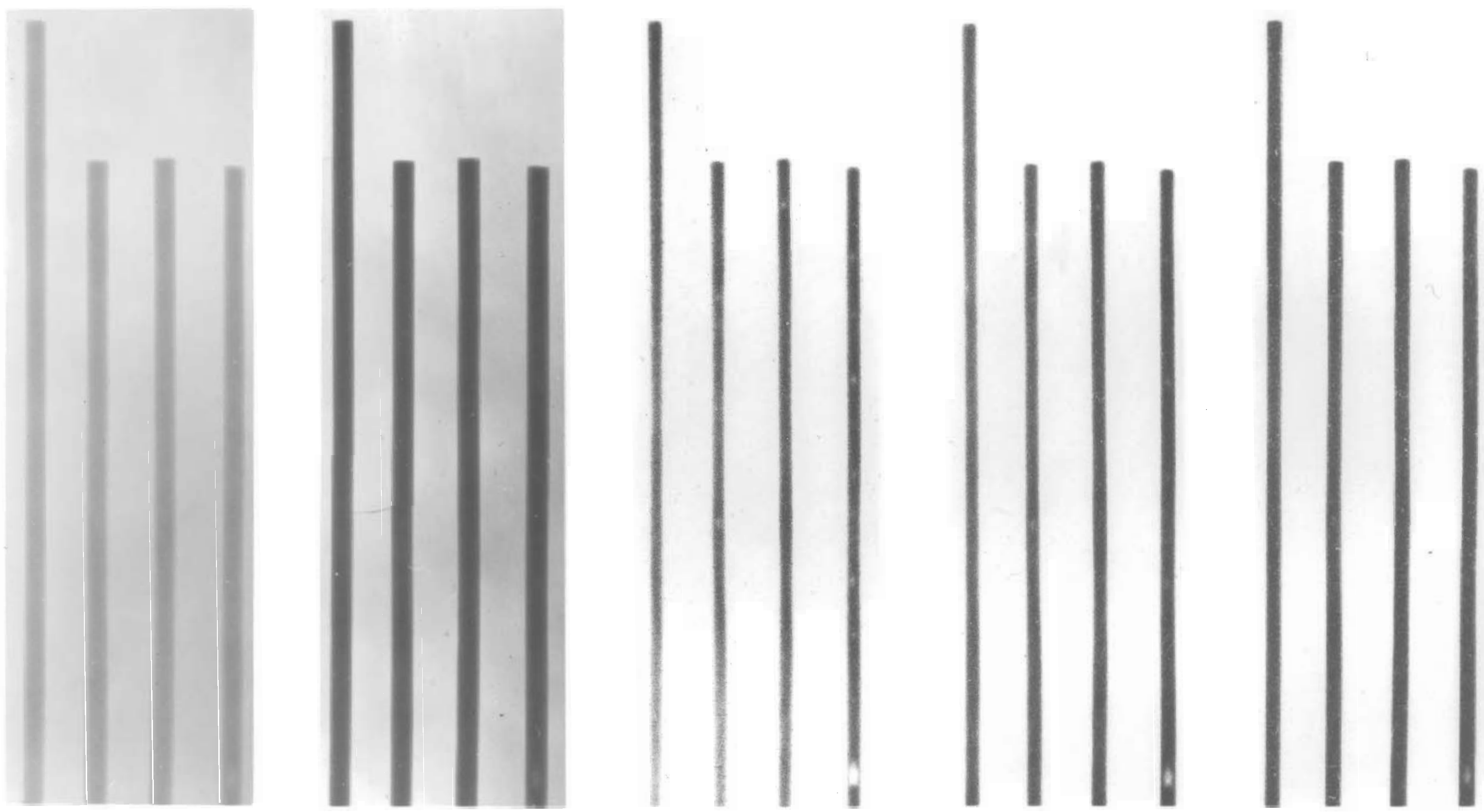


FIGURE 6. FUEL PIN NEUTRONRADIOGRAPH



(a) UNDER EXPOSED | (b) UNDER EXPOSED | (c) OPTIMUM EXPOSURE | (d) OVER EXPOSED | (e) OVER EXPOSED

FIGURE 7. IRRADIATED EBR-II FUEL RODS

in the related subject of holography, the basic equipment was available for use with optical enhancement.

In this process, the negative is placed in the object plane of an optical bench that typically consists of a collimated laser beam, a transform lens, the Fourier transform filter plane, an inverse transform lens and an image plane. By placing special filters in the transform plane it is feasible to selectively prevent the passage of unwanted frequencies through the transform plane. The reconstructed image is thus improved or enhanced.

Data that can be extracted from the frequency transform plane technique include (a) the shape and orientation of the halos around the central position (e.g., the diameter of the central bright area is proportional to the frequency), (b) points far from the origin correspond to high spatial frequencies; low frequencies can be masked out by blocking off part of the focal plane near the optical axis, and (c) the shape and intensity of the brightness pattern surrounding the central image is proportional to the amplitude of the frequency, e.g., this pattern may indicate directional properties in the test specimens. In some cases, marked improvement in edge sharpness occurred due to the masking out of undesirable patterns which had caused a blurred image in the original negative. Although not all of the examples are in the nuclear materials field, they well represent the capability and application of the process.

Homogeneity

Homogeneity is one of the primary characteristics used to describe the results of blending two oxide powders, UO_2+25% PuO_2. It is important to nuclear safety and thermal performance of the nuclear reactor fuel pin that the PuO_2 particles be uniformly dispersed throughout the UO_2 matrix in the 0.220 in. sintered mixed oxide pellet. One quality assurance technique used to determine the accept/reject degree of homogeneity is by visual examination of alpha autoradiographs of the pellets. Although this example has received only superficial treatment by optical enhancement, the data shown are sufficient to indicate the promising value of additional work in this area. Only a low pass filter was used in this study. It should be noted that data can be analyzed from both the diffraction image in the frequency transform plane as well as the final filtered image. The Fourier transform images of two mixed oxide fuel pellets, of varying homogeneity as determined by other methods, are shown in Figure 8. The differences in the diffraction patterns are noted as (a) the shape of the central bright spot, (b) the intensity and size of brightness pattern, and (c) the brightness lobes indicate directional properties. Analysis of the results is still being performed. The three parts of Figure 9 show the unfiltered image and two variations in low pass filtering. Note the apparent reduction of the alpha track noise in the autoradiograph in the matrix material in Figure 9c. The low pass filters remove the high frequency data or noise and result in smoothing of results while the high pass filters remove the low frequencies and result in edge sharpening. The low pass filter may, as in this example, be very small holes in the central area, e.g., 0.010 to 0.100 in. diam.

Keratins (Biology)

Keratins are specialized proteins from animal extremities such as hair, feathers, horns, hooves, skin, etc.[6] Biologists are currently studying the molecular structure of these proteins. One of the techniques used is to obtain diffraction patterns from X-ray pictures and electron micrographs. The researchers resolved an average image of a keratin microfibril by optical image enhancement of an electron micrograph.

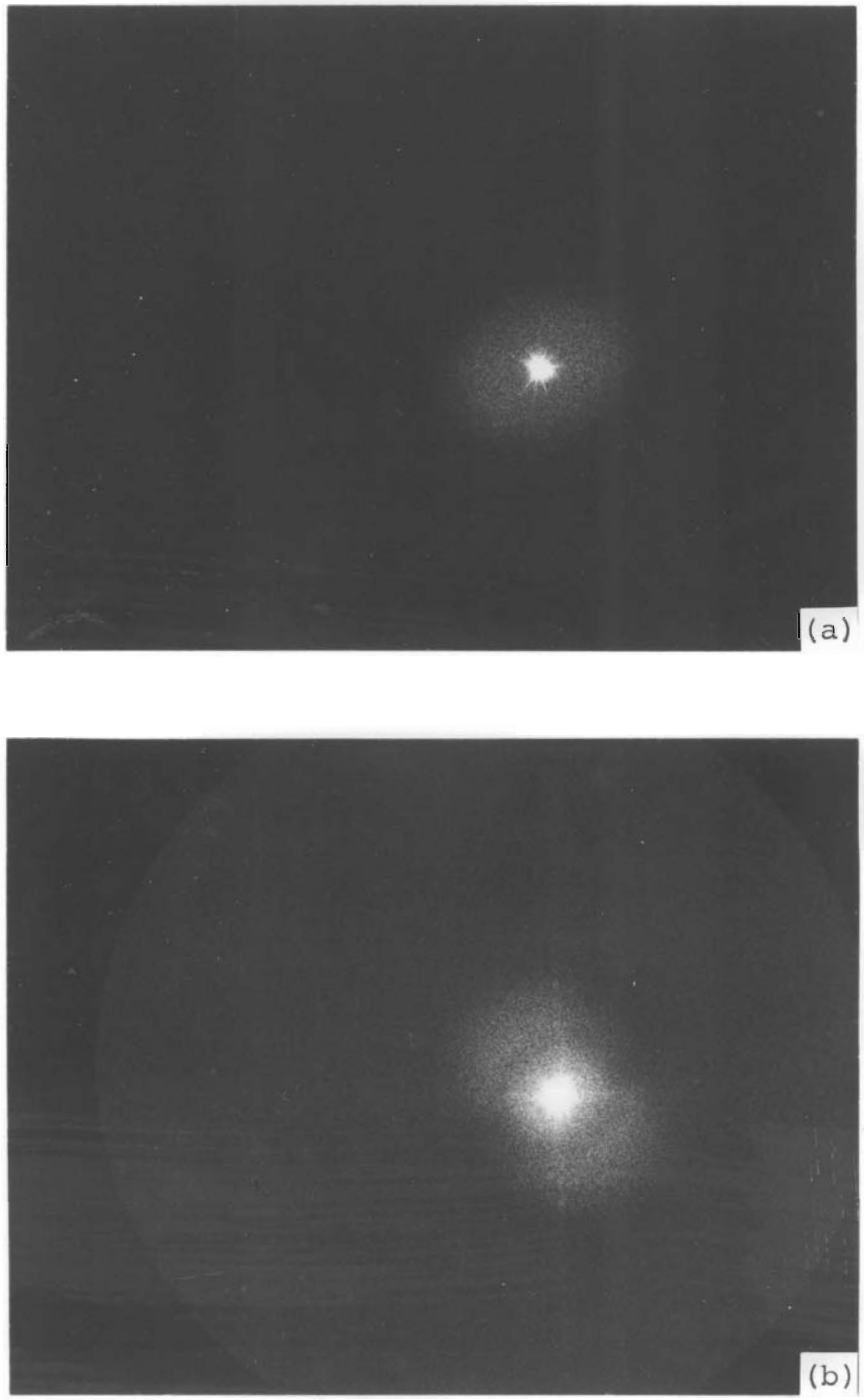
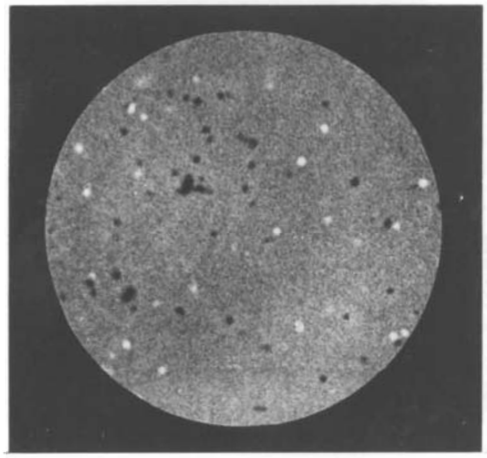
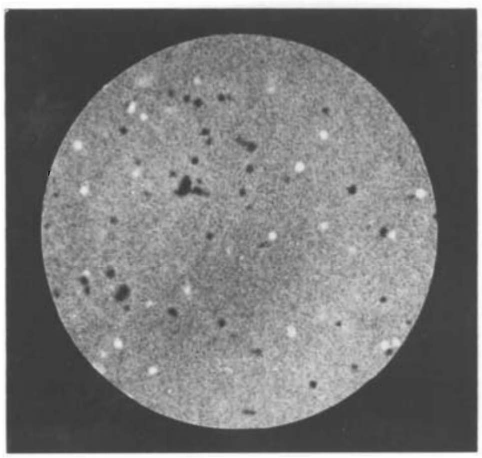


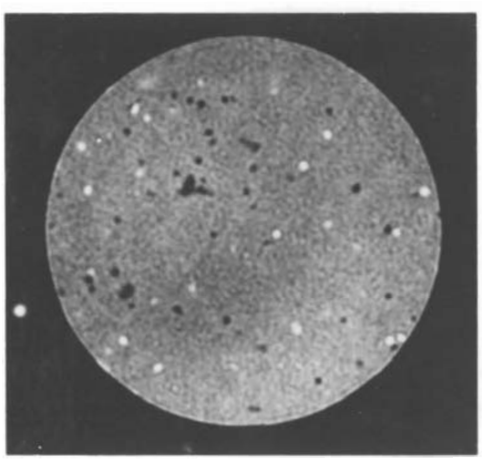
FIGURE 8. FOURIER IMAGE OF FUEL PELLET AUTORADIOGRAPH



UNFILTERED



LOW PASS FILTER I



LOW PASS FILTER II

FIGURE 9. OPTICAL ENHANCEMENT OF FUEL PELLET

The results are shown in Figure 10. Note that the mask or filter used is a modification of the filters shown in the previous section. Due to the lack of original negatives, the resolution of the Figure 10 photographs is somewhat diminished although the effects created by the process are amply illustrated.

Fuel Pin Neutronradiography

Neutronradiography is a powerful nondestructive tool used in the interim examination of irradiated fuels and components. After interim examination, the highly radioactive specimens are then returned to the reactor for additional testing. Thus the data recorded cannot be repeated. Since it is standard practice to make interim examinations at four- to six-month intervals, the changes that occur from one interim result to the next are extremely significant data. The changes that occur may be of two major types: (a) dimensional changes and (b) structural changes in the fuel column such as the formation of central voids and spaces between fuel pellets. Accurate measurements of these changes can be made if standards are introduced in the original neutronradiographs.

A series of under to over exposures of an original neutronradiograph of an irradiated fuel pin are shown in Figure 11 (no enhancement). Some improvement in results, by photography alone, are observed. (This is similar to photographic enhancement but without the elimination of undesirable matrix densities or slices.) However, there is a major further improvement (Figure 12) by the use of a special line filter in the optical enhancement system. This filter sharpens both vertical and horizontal lines, thus making measurements much more accurate, and confirming and defining the presence of the fuel pellet structural changes. Additional filters need to be tested and evaluated on this specimen. Details of this preliminary work are reported by F. R. Reich.[7]

Ocean Surveillance[8]

Aerial surveillance of the ocean is often used for anti-submarine warfare purposes. The application of Fourier transforms to automatic pattern recognition is shown in this example. Figures 13a and 13b show the actual image of the ocean and the resultant diffraction pattern, respectively. Figures 13c and 13d show a similar patch of ocean with a ship's wake and the corresponding diffraction pattern. Note that the wave motion is coarser in Figure 13a than in Figure 13c, which results in a slightly different diffraction pattern. A ship's wake is very sharply noted by the presence of the two parallel lines in Figure 13d. Only very careful observation would have revealed the wake in the original negative.

COMPUTER

Introduction

Very current examples of computer image enhancement have been distributed nationwide via the Mariner pictures of the planet Mars and enhancement of the numerous moon surface pictures. These examples have provided some of the main features of computer processing, including filtering, subtraction, and removal of system noise. In addition, considerable work has been done in the medical field, although no examples are provided in this report. The two examples shown briefly illustrate the capability of computer enhancement.

(a) Photomicrograph of irradiated UO_2, and
(b) Typical Mariner photographs.

Other typical computer enhancement operations that may be performed within the computer include smoothing, edge detection, edge sharpening, abstraction, correlation, and pattern matching.

The computer enhancement process is somewhat similar to the photographic method in terms of gray scales. The negative

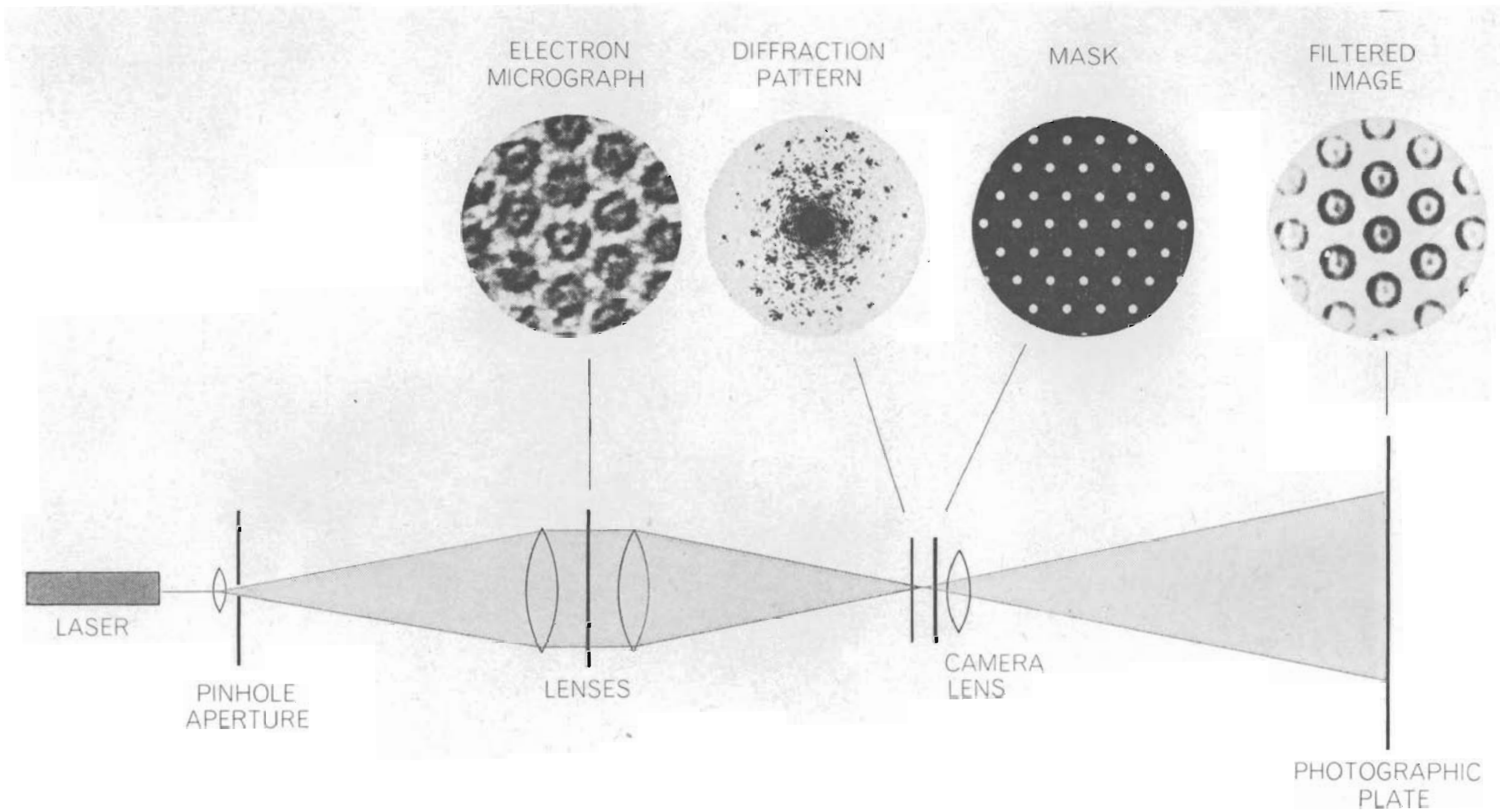


FIGURE 10. KERATINS-OPTICAL ENHANCEMENT

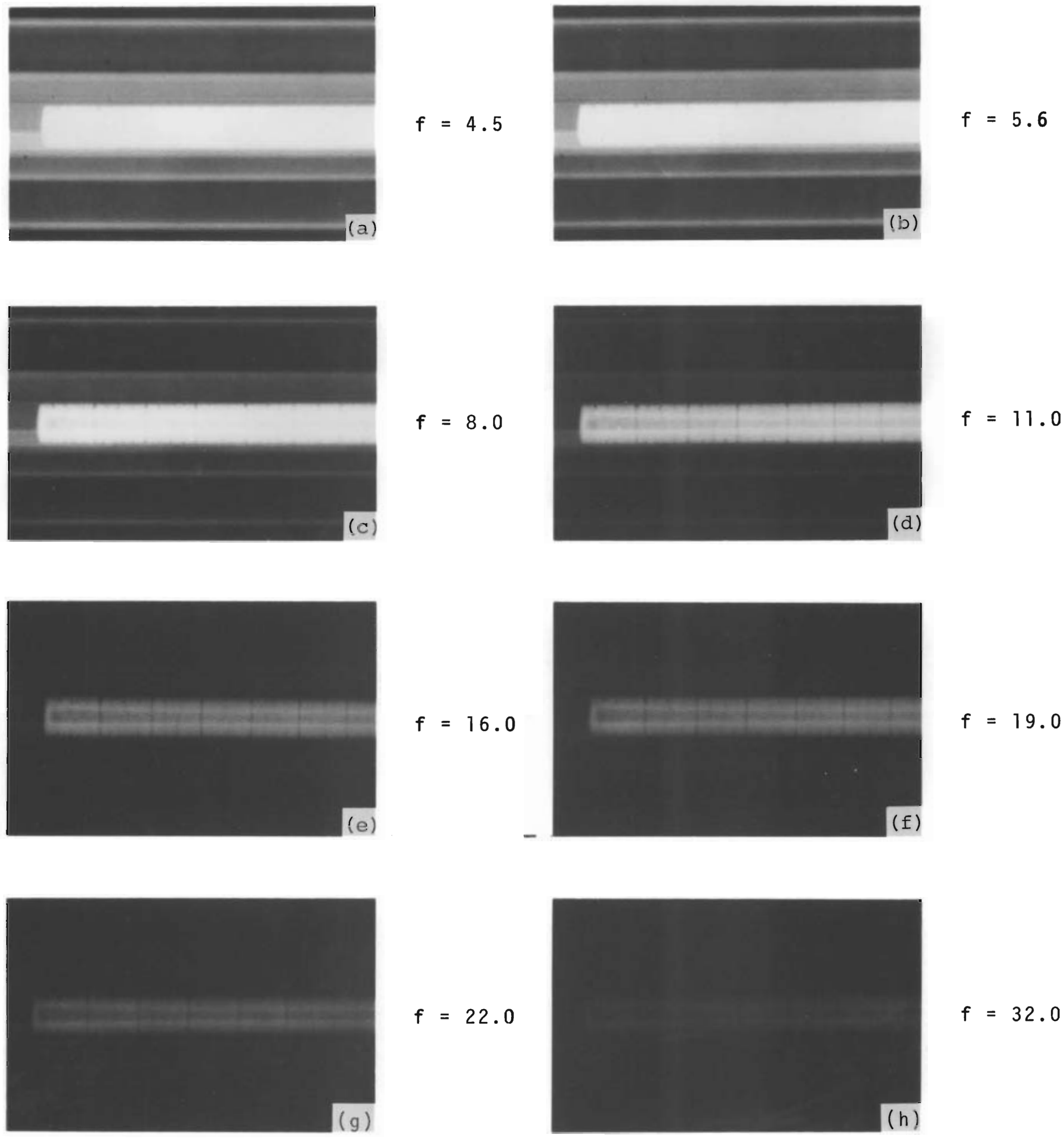
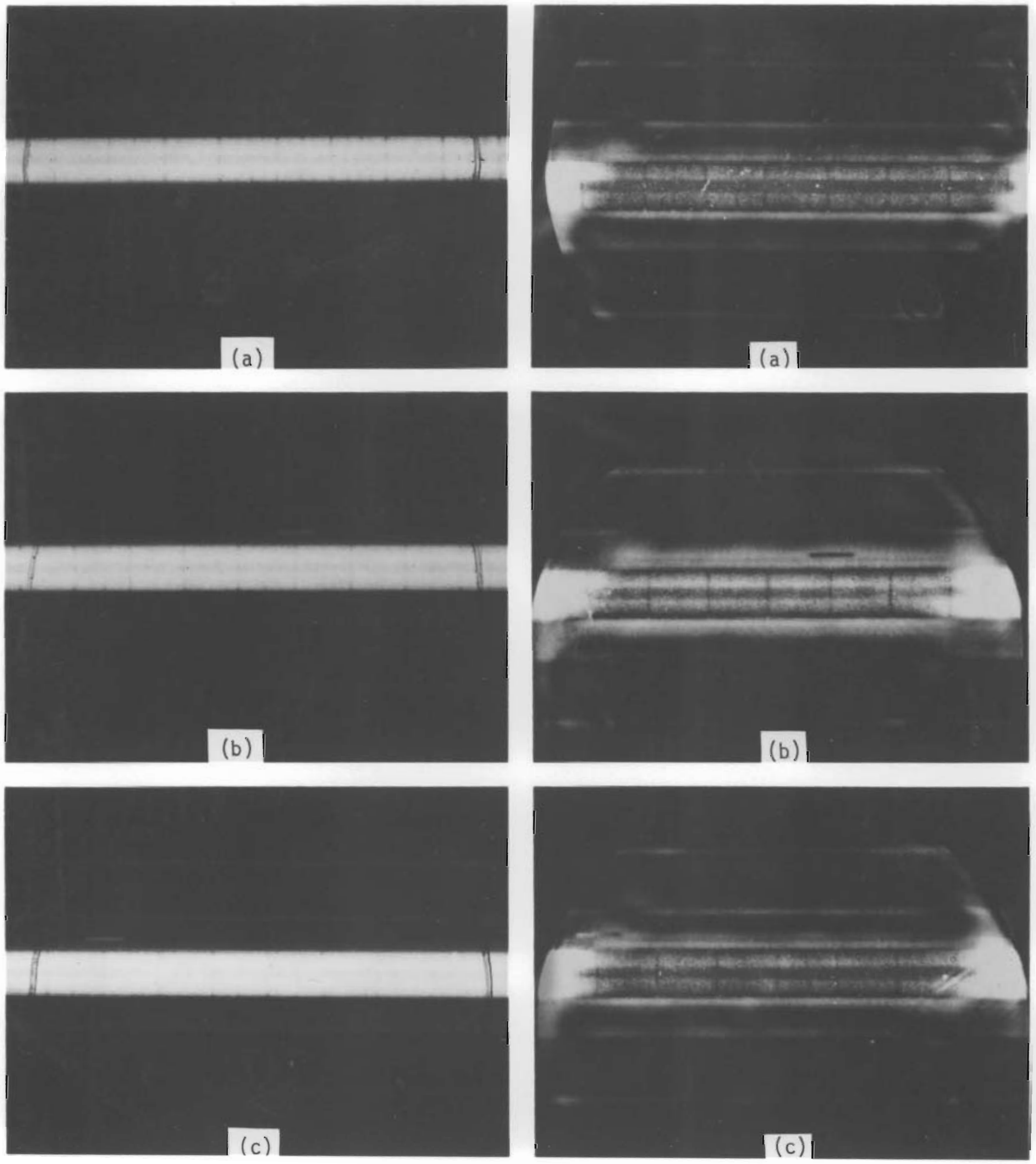


FIGURE 11. IRRADIATED FUEL PIN - UNDER TO OVER EXPOSED (SHUTTER SPEED 1/30 SEC)



NEUTRON RADIOGRAPH IMAGES

NEUTRON RADIOGRAPH PROCESSED IMAGES

FIGURE 12. IRRADIATED FUEL PIN - OPTICALLY ENHANCED

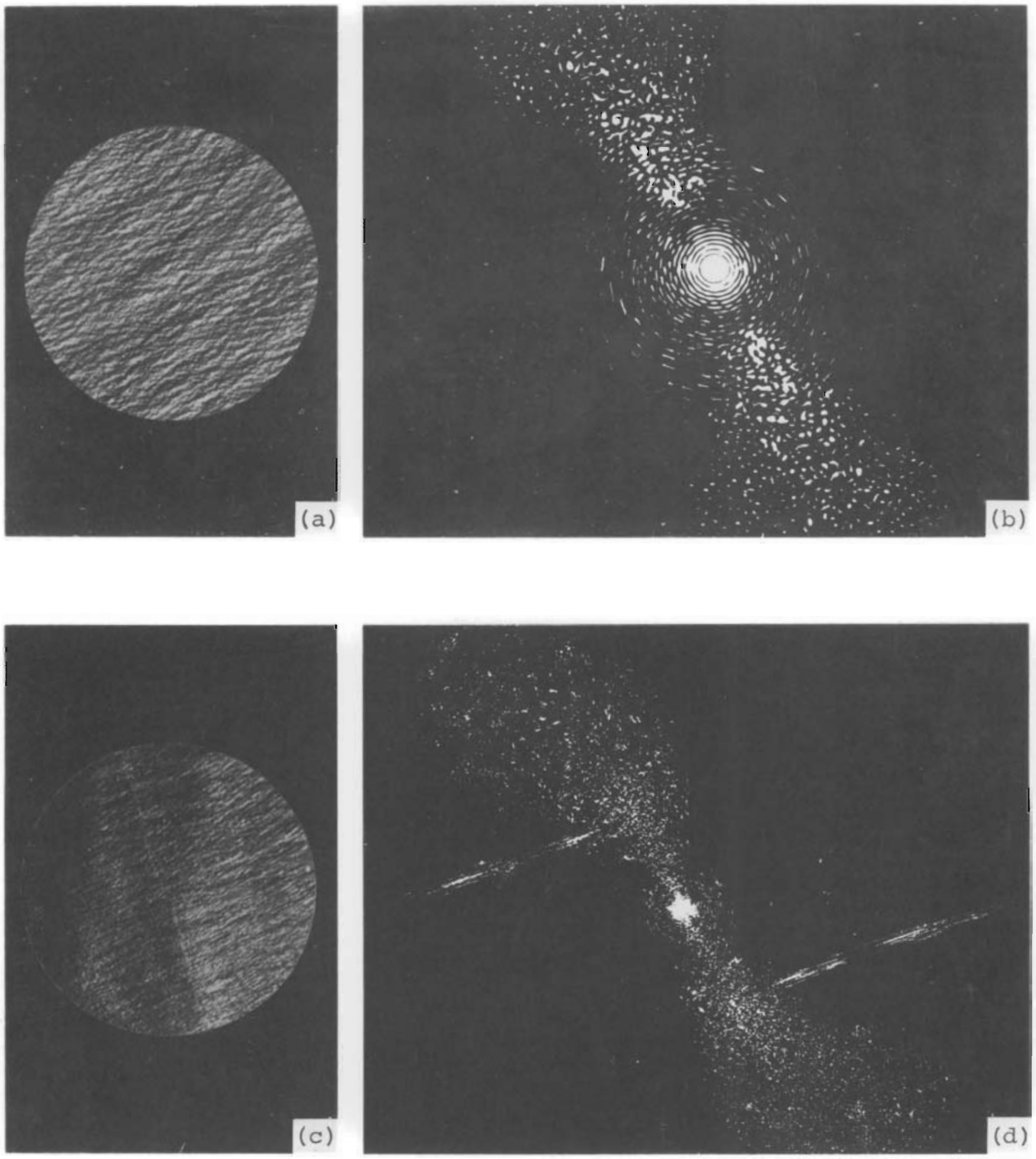


FIGURE 13. OCEAN SURVEILLANCE

is scanned and the resultant signals which are dependent on the gray scales are converted to digits which are then manipulated within the computer and displayed on a CRT (cathode ray tube). When the desired data are observed, the computer display is converted to a photographic print. This process is described in greater detail in the appendix.

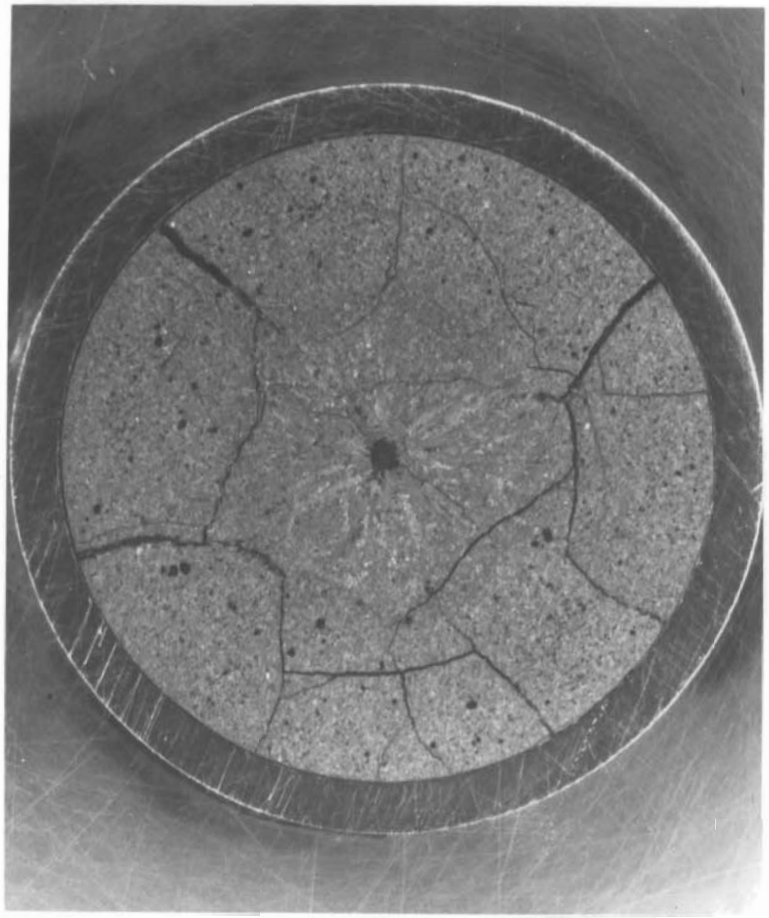
Irradiated UO_2 Cross Section

Pelleted UO_2 is the fuel form used in many nuclear power plants. These $\sim$1/2-in. pellets are loosely encased in thin-walled stainless steel or zirconium metal tubes. After exposure in the reactor, the tubes containing the pellets are cut open for examination to determine the performance limitations of the fuel pin and its components. The cross section is then polished and etched and examined by microscopy. An example of the original unenhanced photomicrograph product is shown in Figure 14a. Ideally, the computer would process data from the original negative. In this case, a negative had to be made from the positive submitted, which will account for some loss in data. The negative was scanned and the data digitized for analysis.

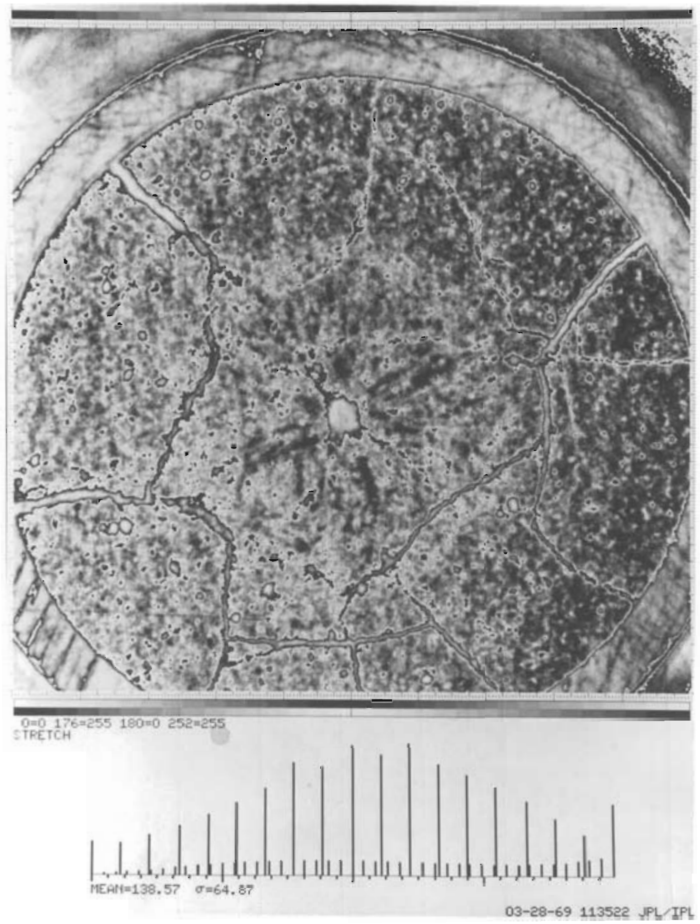
Three examples of the capabilities of computer analysis are shown in Figures 14b, 14c, and 14d. In these examples, the gray levels or densities are reduced to numbers. It is then feasible for the computer to emphasize any gray level or groups of gray levels as shown on the spectrum at the bottom of each figure. Note that the spectrum of emphasis is different in each figure and the corresponding picture produced shows the effects of this emphasis. The technique of reverse contrast is also indicated in Figures 14e and 14f, thus, using a video console for viewing, it is possible for the researcher or engineer to very flexibly manipulate the areas of interest such as adding, subtracting, reverse contrast, etc., to more clearly reveal new or confirm suspected data.

Mariner-Mars

Space technology has produced major breakthroughs in data handling techniques. Photographs of the moon and Mars are digitized and telemetered to earth for analysis and evaluation. Computer enhancement of Mariner photos brings out details that were not clear in the original data. The Mariner space explorer sent to earth about 200 pictures of the surface of Mars. One as-received original photo of Mars' surface craters[9] is shown in Figure 15a. Detailed examination of this picture reveals a faint basket weave pattern caused by electronic noise. Computer analysis reveals the pattern shown in Figure 15b. The computer analyzes this pattern and converts the pattern to a numerical value which is then subtracted from each of the 658,240 elements of the original picture. The results are shown in Figure 15c. Another computer analysis is used to compensate for the smearing due to the vidicon tube. The results of this analysis are shown in Figure 15d which is a much sharper image than the original.

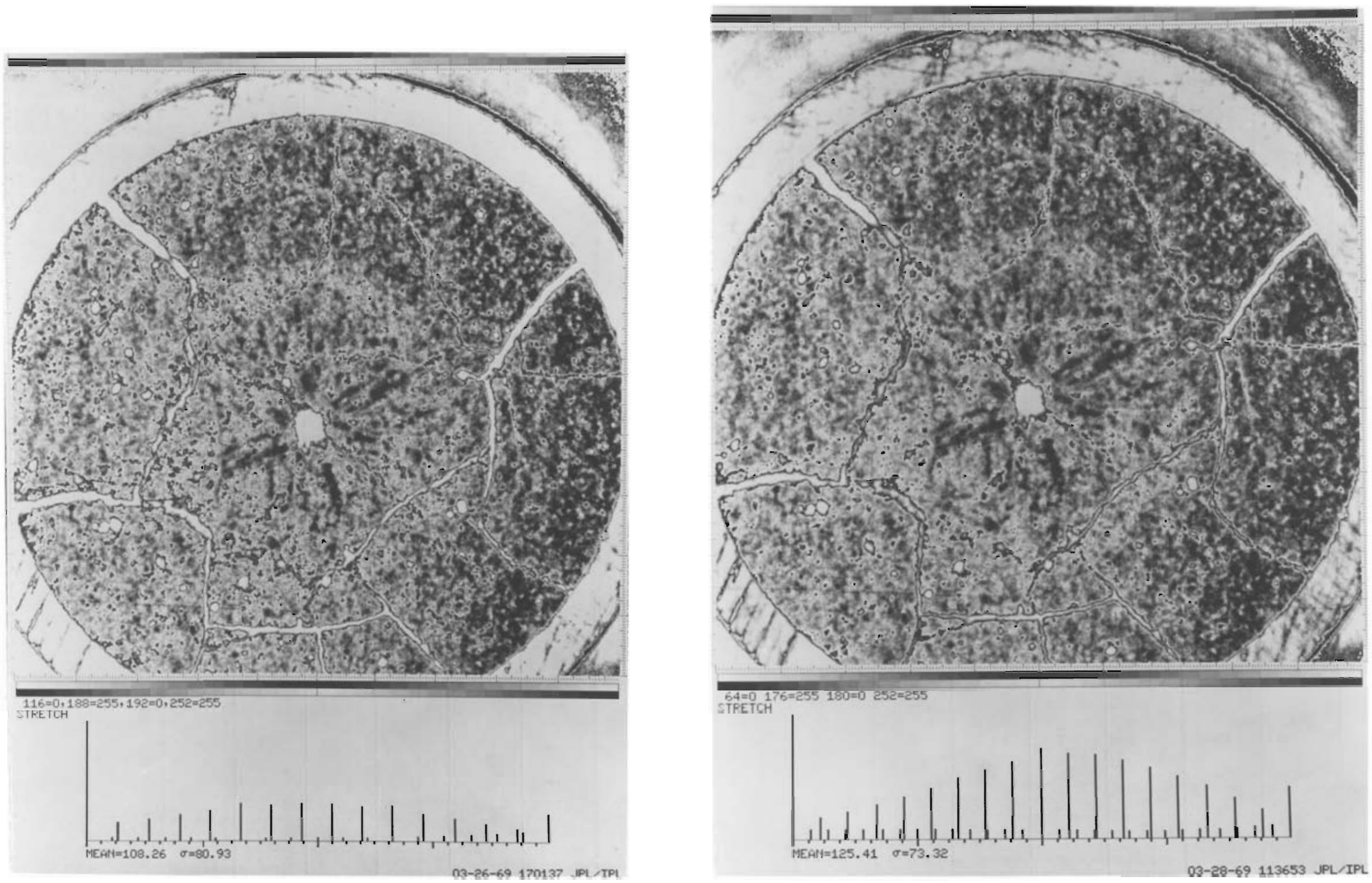


A



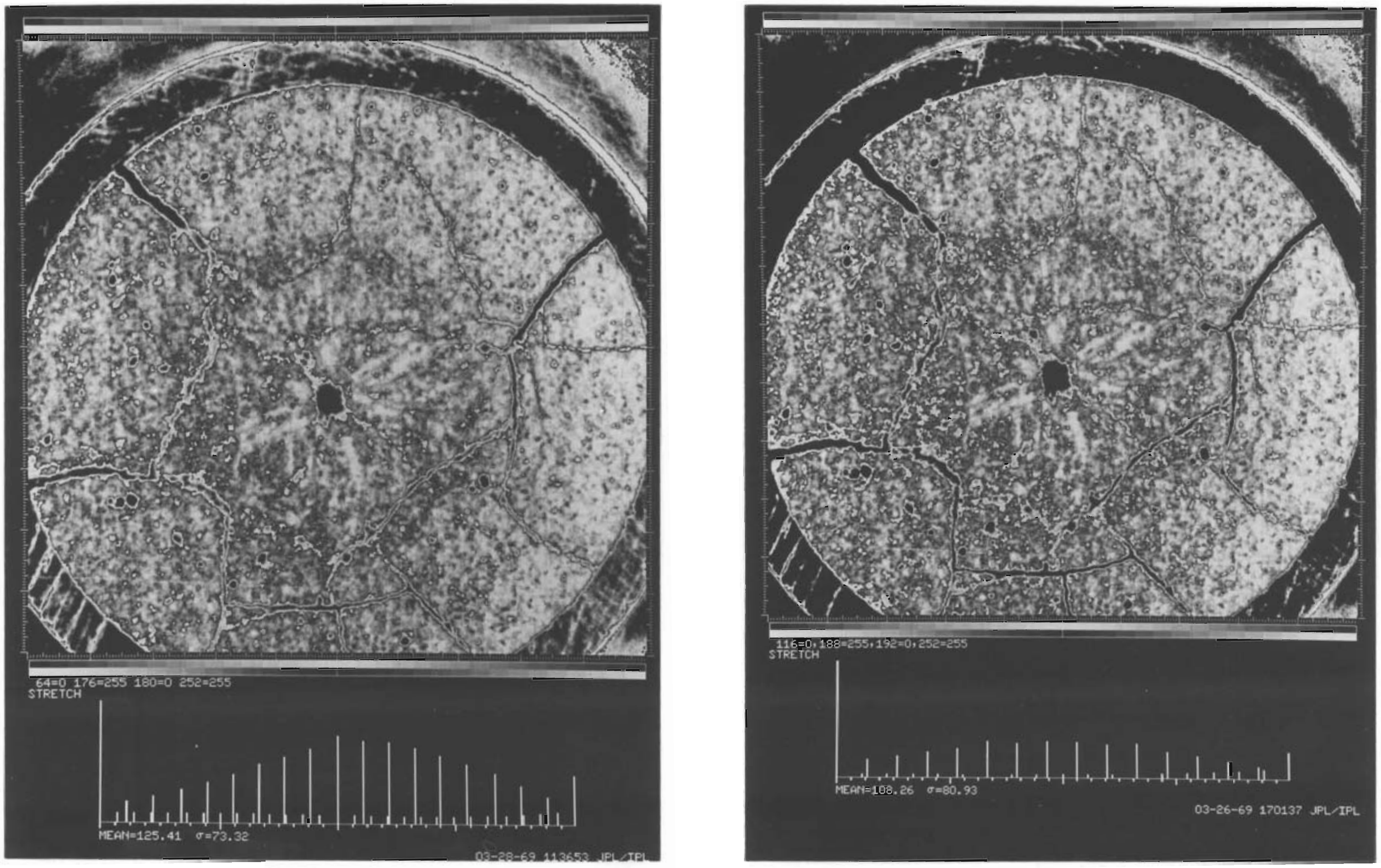
B

FIGURE 14. IRRADIATED UO_2
A - NORMAL B - ENHANCED



C D

FIGURE 14. IRRADIATED UO_2 - COMPUTER ENHANCED



E F

FIGURE 14. IRRADIATED UO_2 - COMPUTER ENHANCED

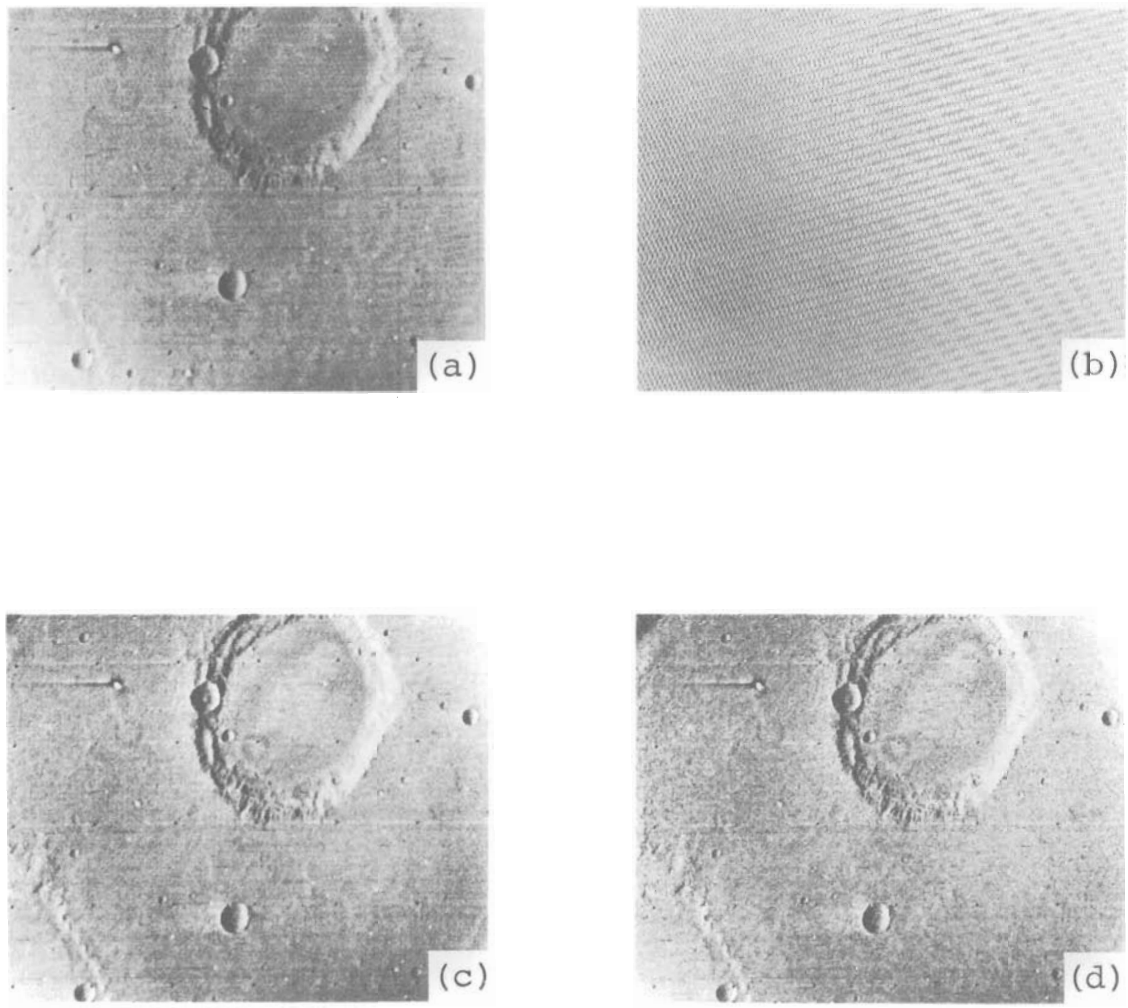


FIGURE 15. MARINER-MARS COMPUTER ENHANCEMENT

ANALYSIS OF RESULTS

The FFTF fuel development program has rigorous requirements in the technical areas of irradiation testing and nondestructive testing for high performance reliabiility. The process control of the fabrication of large quantities of UO_2+25 wt% PuO_2 into fuel pins requires analytical methods and nondestructive tests (NDT) such as X-ray that provide rapid, precise, and accurate results in order to maintain the required flow of materials. These fabrication processes also produce the materials and components for the multimillion dollar irradiation test program. Small expenditures for image enhancement in these areas will be repaid manyfold in dollar and schedule efficiency.

There are some general comments regarding interpretation of results that equally apply to all three enhancement methods. How do we get the most out of the photographic test results? Image enhancement can be either a pure purchased service function or a part of a standard laboratory facility. The results are optimized by providing close coordination between the originator of the image or negative and the image processor. Battelle-Northwest discussions with the image processors indicated that improved negatives would increase results that may now be relying on image enhancement alone to reveal or clarify the relatively poor data on a negative. The improvements would include such factors as:

- Proper film for the conditions
- Use of standards
- Correct exposure for regular negatives
- Correct X-ray or neutron-beam characteristics for X-rays or neutronradiographs.

The coordination between the data originator and the image processor is considered a vital factor. There is a high degree of process flexibility in all three processes which can either enhance some, all, or none of the features that are being interpreted. These processes require some arbitrary assumptions to be made such as choices of colors and density levels that may require additional detail. The use of colors reduces the uncertainties of objective decisions that may prevail with gray tone variations alone. These assumptions could definitely affect the interpretation such as actually choosing the wrong density levels to be emphasized. It has been shown in photographic enhancement practice that an initial test series of enhanced photographs that cover the density spectrum will reveal trends in results. This is then followed up by a larger number of density slices within a given density range that can enhance the more interesting features. The tremendous flexibility of the computer is probably the best example where close coordination is vital. It is strongly recommended that side-by-side comparisons of the original negative and the enhanced results be made to clarify and confirm observed data and to avoid misinterpretation due to artifacts and system noise that occasionally are present.

In the initial interest in image enhancement the originator may have some idea of the types of results desired. Obviously every negative should not be enhanced. Likewise, all enhanced negatives will not reveal new data. Many negatives reveal vague or unclear areas. With enhancement, the uncertainties become certainties and in some cases new observations are made that could not have been made previously. Examples of these were given in the previous sections. It has also been observed that the suspected observation on one negative will lead to clarification by the examination of related negatives in a test series or may lead to further negative preparation using slightly different test or preparation conditions. There are also possibilities of artifacts, noise or other discrepancies occurring which can be eliminated by verification through other negatives or by proof of observation by an independent determination method, e.g., destructive examination of a fuel rod containing internal flaws or by checking specific areas on a negative by a microdensitometer.

A thorough understanding of these processes further suggests to the originator in areas such as X-rays or neutronradiographs, that two or three exposures will permit examination of more than one critical area, rather than overexposing the entire negative due to the requirement of one part, e.g., one exposure emphasizing the thin-walled stainless steel fuel pin (medium density) versus one exposure to emphasize the UO_2+PuO_2 fuel pellets (high density). It has also been demonstrated by the computer technique that through the use of identical exposures of two, three or more negatives that minute differences (film grain noise) between the negatives can be filtered by the computer, thus revealing improved results.

The use of standards in all negatives would further improve the quality and quantity of data. Where feasible, the negative should contain density standards that cover the spectrum of density levels anticipated in the negative. Or, if the data to be obtained is dimensional, then precisely measured standards should be photographed at the same time as the unknown. The preparation and testing of these standards will also reveal the specific capability of each enhancement process. As noted in the text, each process has unique capabilities and should be used according to the optimum application.

Some relative advantages and disadvantages of the three systems are tabulated below:

	Advantages	Disadvantages
Photographic	Fairly cheap Demonstrated status Low capital investment	Lacks resolution (may not be limiting) Arbitrary assumptions
Optical	Capable of high resolution No computer	Lacks flexibility Lower accuracy
Computer	Capable of high resolution Direct data action without photography High flexibility	Expensive Large equipment requirements

These three methods of image enhancement provide an excellent way to convey to an engineer or researcher the qualitative implications of his preliminary assumptions. It may save unnecessary analysis of incorrect guesses. Such reductions in time and tedious human effort permit data processing, which a few years ago was impossible, and, for many technically trained people, not even within their contemplation. The catalog of application of these methods is spectacular. Beyond the illustrations shown, these methods have rapidly growing use in education, medicine, and art (e.g., Walt Disney). This new technology literally makes it feasible to "see" the invisible, enhances the imagination, and permits experiments to be done with flexibility and rapidity that heretofore were prohibitive or impossible. Thus the extraction of additional data at relatively low cost from expensive and long-term experiments can reduce the number and cost of tests and, therefore, should be pursued with vigor. A diligent effort is necessary by management to keep abreast of these technical gains and to apply them as they are developed.

ADVANCED DEVELOPMENT

Very rapid progress is being made in the field of data processing. Many new concepts and examples of hardware application are under development. Current scientific trade journals contain fairly numerous examples of new equipment for this field. The computer and its associated display console provides one of the major avenues for advancement. A few examples are provided to illustrate the concepts being developed. One of the best methods to appraise the status of this field is to review the conference proceedings in References 2 and 10.

The reader by this time should be concluding that an ordinary negative is no longer a final product of a test result but is now considered to be an interim result that may be further processed. However, every negative should not be enhanced. In some examples of advanced technology, the original negative is bypassed and the enhanced negative becomes the final product. One example is shown in Figure 16. The originating sensor, such as an electron microscope, sends its data directly into the computer, thus bypassing the original photography. These data are then processed or stored by the multiple means capable in a computer such as contrasting, filtering, subtraction, edge sharpening, etc. The supporting facilities to the computer include a display console which permits a real time observation of the changes being made by the computer. This operation would have been very time-consuming by other methods. In a secondary facility, the data could be stored for comparison with other samples to be studied at a later date. This storage and comparison analysis would equally apply to direct data manipulation or to data stored from negatives such as neutron-radiographs which do not lend themselves to a direct computer input. Minute differences between similar tests can be analyzed by the computer. Many more tests would have been required to reveal the same trend of results by current methods. Initial hardware prototypes should be available for demonstration in one year or less.

A second type of advanced concept is related to the optical processing method and is shown in Figure 17. This system combines the digital and optical methods and uses computer storage of data that is retrieved and displayed on a CRT. The CRT screen then acts as a negative in the standard optical enhancement process previously demonstrated. This hybrid system provides rapid retrieval of stored data for analysis or comparison. Two further additions to the system shown in Figure 17 would include (1) increased flexibility of filter changes that would perform various types of operations, such as a small console that permitted rapid on-line filter changes by the operator, and (2) an output display console that would allow direct observation of results with the added flexibility of observation of changes from either the computer input or the filter or mask used in the optical system.

There are two other closely allied fields of image enhancement that were not discussed here but may use the techniques described. These techniques include the new and expanding fields of holography[11] and infrared photography. Both of these fields have a promising future in the materials area and should be further explored. Stress patterns in fuel pin clad materials are already being studied by holography at Argonne National Laboratory and at Battelle-Northwest. Infrared may have application in nondestructive testing or examination of irradiated materials.

The use of image enhancement has numerous potential applications both within the FFTF fuel development, fabrication and postirradiation examination and throughout the plant construction. Specific examples include nondestructive examinations

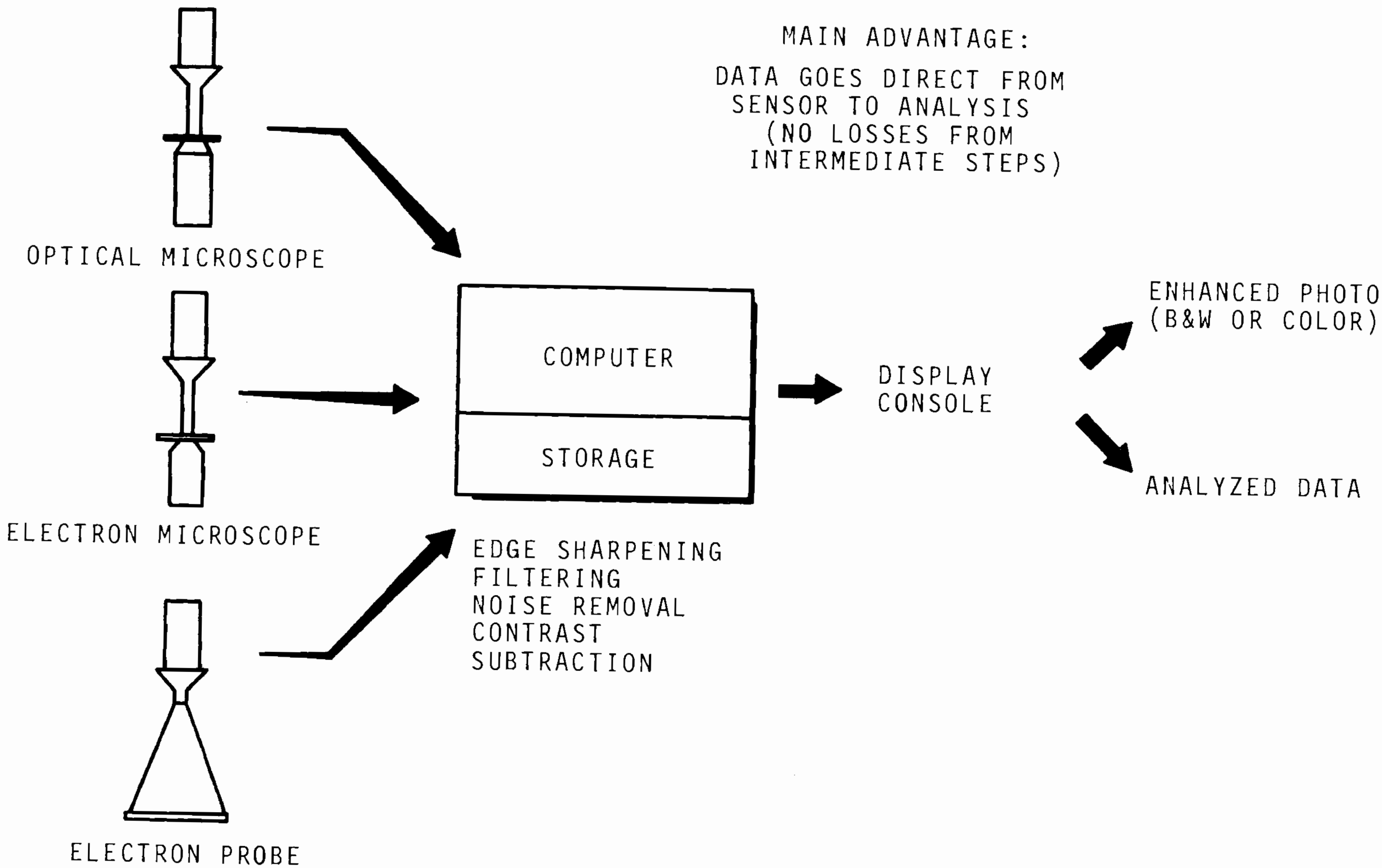


FIGURE 16. ADVANCED DATA ENHANCEMENT-COMPUTER

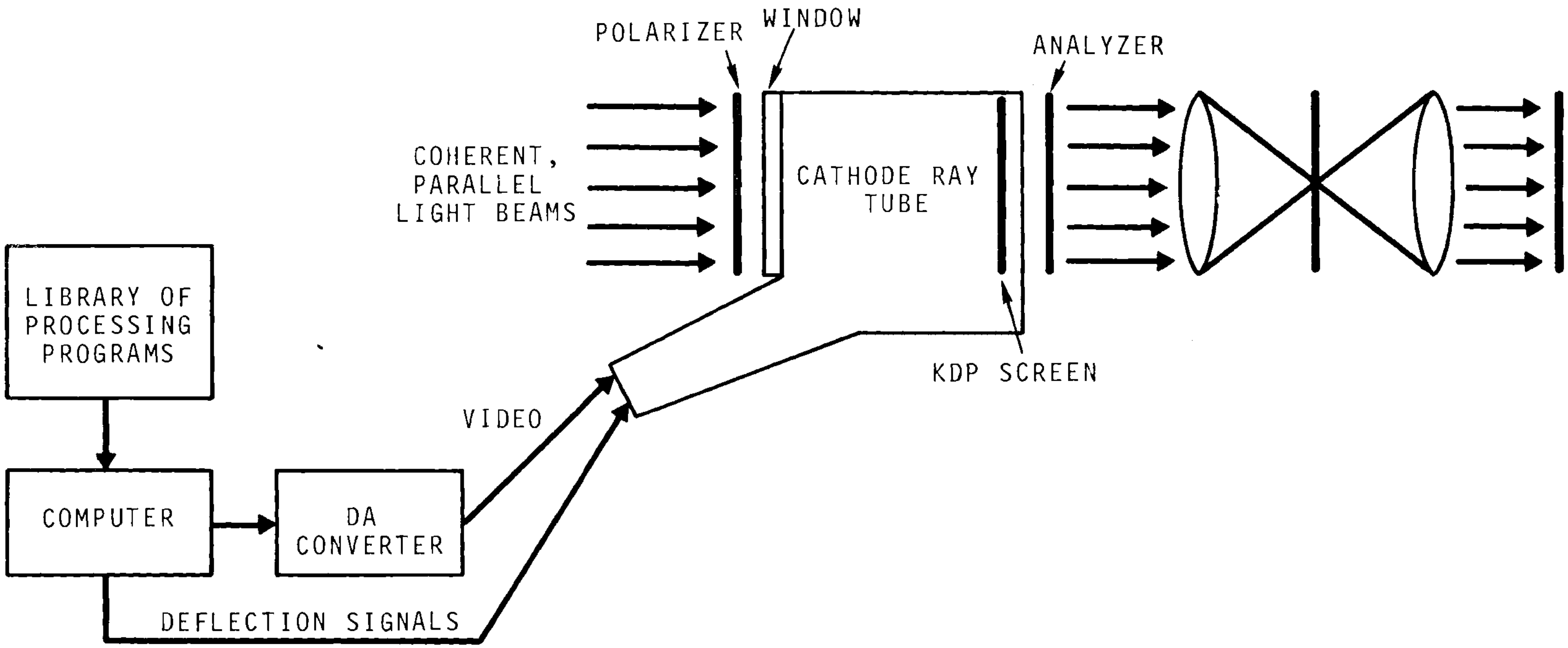


FIGURE 17. ADVANCED DATA ENHANCEMENT-OPTICAL

of fuel pins for weld defects, alpha autoradiographs for homogeneity, gammagraphs for Pu concentration, X-rays of pins for verification of internal components, and neutronradiographs for interim and final examination of irradiated fuel pins. In addition, image enhancement can be used, where necessary, in any interpretation of X-rays, such as large vessel or piping welds, pump castings, in the FFTF construction. A microdensitometer should be evaluated as an additional tool for use in an enhancement system. The image processing developments currently in progress should provide highly flexible, real time, data handling methods that expand the volume of results for the dollars invested. Advantage should be taken of these huge efforts expended by DOD and NASA in the development of the theory, models, and full-scale hardware for this phase of data processing.

ACKNOWLEDGEMENTS

The support and encouragement of E. A. Evans provided the motivation to explore the potential of image enhancement to nuclear materials. Many useful discussions with G. A. Last, R. E. Mahan, R. B. Smith, F. M. Smith, and F. R. Reich yielded a more rapid appraisal and understanding of the technical aspects of image enhancement.

APPENDIX

METHODS OF IMAGE ENHANCEMENT

The three methods of image enhancement that show immediate potential for use on the FFTF program are (1) photographic, (2) optical, and (3) computer. All of these methods currently use the negative or transparency as the source of data. It should be noted that substantial losses in detail occur on every reproduction of a negative; therefore, original negatives are the recommended starting point for the processes. Each method is described below in terms of a diagrammatic sketch, equipment, a descriptive outline of the process and the status of development.

Every technical photo interpreter is familiar with the feeling that more information is buried in the photograph than can readily be seen with accuracy and confidence. When one considers that in one square inch of film, resolving 50 optical lines per millimeter and 64 levels of gray, there are 400×10^6 information bits, this is not unreasonable.[5] Other typical references include (1) a TV screen has about 525 lines over the full face of the screen or approximately 50 lines per inch. This resolution is poor; (2) the best CRT (cathode ray tube) can produce 200 lines per inch; (3) the best film can produce 40,000 lines per inch.

Photographic Method

Information is recorded in photographs in the form of optical densities. The fundamental image characteristics the interpreter uses for identification and analysis of photographic data are size, shape, pattern, texture, shadow, and tone.[5] In photographic engineering terms, variation in the tone, or density scale, is the common factor which constitutes the whole image. The spatial arrangements of these density variations form the image, and make possible the perception of size, shape, pattern, texture, and shadow. Processes which suppress or amplify very small tone differences, which are just on, or even below the threshold of visual recognition, can be utilized to enhance the primary image characteristics, enabling the interpreter to extract additional information. Extracting image data at the threshold of interpretability varies with the knowledge, eyesight, and experience of the interpreter, but in any case requires subjective judgment at some point. Image processing by photographic means can reduce or remove many of these subjective uncertainties. The degree of enhancement possible is ultimately limited to the qualities of the original negative or image. No new data can be generated that are not on the original film.

Basically the photographic enhancement process consists of precision photography. The detailed processes used vary slightly and in some cases are considered proprietary information. Initially, as a typical example, an estimate is made of the range of photographic densities that exist on the specific negative. A normal range is about 0.4 to 1.6 on the characteristic Herter-Driffield curve of density vs. exposure. Overexposed film flattens on the characteristic curve at approximately densities of 1.6 to 2.0 and underexposed film has densities from 0.1 to 0.4. One of the simplest methods of making small density differences perceptible is to print the image at high contrast. However, all other tones present are then converted to opaque shadow densities. As seen in Figure A-1, the most data, or variations in density, which permit enhancement, occur in the straight line portion of the characteristic curve. Very little enhancement can be obtained from underexposed or overexposed film.

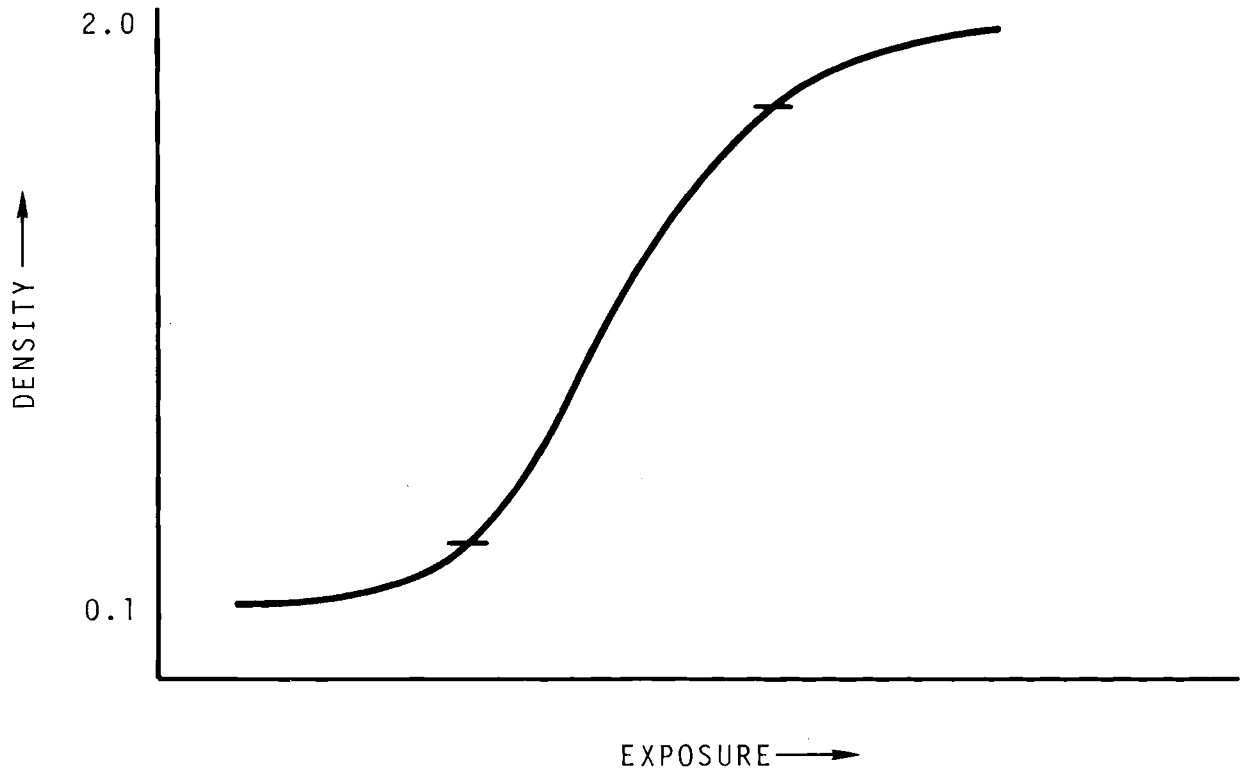


FIGURE A-1. TYPICAL HERTER-DRIFFIELD CHARACTERISTIC CURVE

It is feasible through this precision photography to reduce the tones in a normal negative to 16, 32, 64 or up to 300 density increments. Usually most information is derived in the 8 to 32 range. One of the typical means of suppressing unwanted density levels in multispectral images is by masking. This method also results in enhanced densities. Another method, unsharp masking, is a variation for enhancing fine image detail and shadow areas. The results of these tone separations or density slices yield 8, 16, 32, etc., separate negatives which are then individually examined and printed or carefully registered and printed as a composite. At this stage, the interpreter discards the tones that confuse or disguise the result. The photographic method is shown in Figures A-2 and A-3.[12] Up to this point all operations have been on a black and white basis. As each density slice or derivation is made, it is feasible to assign an arbitrary color to each one. Thus another degree of enhancement occurs since minor changes in density may be shown as sharply contrasting colors. After the choice of colors is made the colored print is produced by a die transfer process as either an individual print or as a composite. In this way, previously suspected images or vagueness of the existence of certain image features are more distinctly displayed. Since these color choices are arbitrary, it is important that the photographic engineer closely coordinate with the research interpreter. It is recommended that a normal image be examined side by side with the enhanced image.

For a relatively modest expenditure, high quality timing, developing, and registering equipment can be obtained for black and white results. For increased resolution, greater detail, and color enhancement, additional equipment in the form of a densitometer, enlargers, automated developing and printing equipment are required. Some industrial groups have recently completed consoles that further add to the flexibility of the

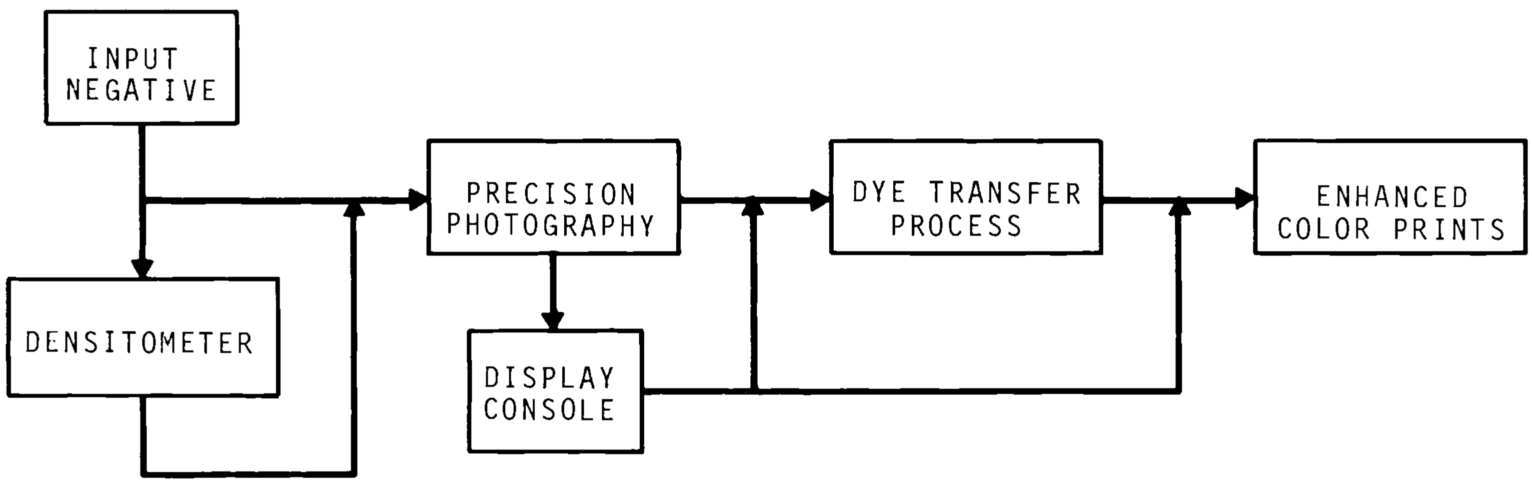


FIGURE A-2. TYPICAL PHOTOGRAPHIC IMAGE PROCESSING SYSTEM

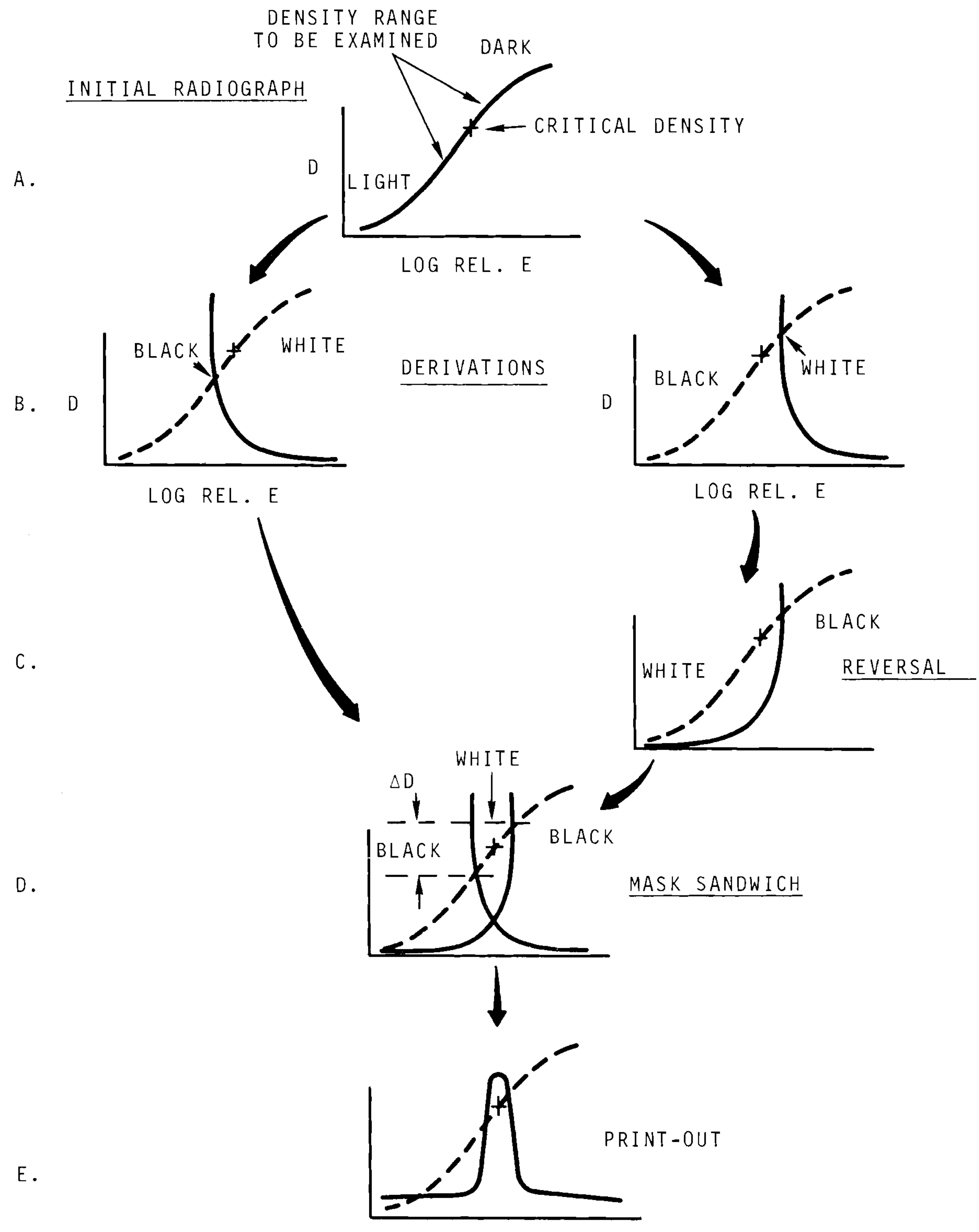


FIGURE A-3. PHOTOGRAPHIC EXTRACTION TECHNIQUE (SCHEMATIC)[12] interpreter. The time required for processing a bare negative to enhanced results varies from a few days to a few minutes on the advanced design consoles. It is thus feasible to consider this technique in terms of almost real time data that potentially could support manufacturing operations such as reading nondestructive X-rays as well as sophisticated R&D programs. Principal factors favoring the photographic method are (1) increased image contrast, (2) filtering unwanted density levels or tones, (3) economy, (4) availability, and (5) reasonable processing time.

The equipment requirements vary widely depending on the degree of enhancement desired. Typical available commercial image enhancement equipment include the Quantimet, Isodensitometer, and Isodensitracer.

In summary, photographic images frequently contain useful information that cannot be detected visually. Among image processing techniques, photographic film provides an economical and rapid means for enhancing imperceptible density variations, to reveal significant data.[5]

Optical Method

Images can also be described in terms of their spatial frequency components. Just as complex electronic wave forms can be broken down by a spectrum analyzer into frequency components, so can a photographic image be optically broken down into a two-dimensional pattern of frequency components.[13] In the electronic case, one gets the Fourier transform of a wave form, while optically one gets a two-dimensional Fourier transform of an image. A two-dimensional Fourier transform is similar to an X-ray diffraction pattern. In electronics, frequency sensitive devices such as filters and amplifiers are used to eliminate noise and otherwise change the frequency content of the signal. Similarly, by optical methods, frequencies in a photographic image can be physically modified through spatial filtering. Such processing is possible because the two-dimensional Fourier image transform is actually a physical array of light points on a plane in space. Each light point is equivalent to a particular spatial frequency and the brightness of that point is proportional to the amplitude of the corresponding frequency. To vary the characteristics of an image transform, it is necessary only to interpose a light filter in the transform plane. By selecting a filter with the proper optical density and pattern, one can selectively prevent unwanted frequencies from passing through the transform plane. Thus a coherent optical filtering system can successfully eliminate many types of photographic image problems. The degree of filtering success depends on the quality of the lenses used.

A typical optical enhancement system is shown in Figure A-4. The negative or film transparency is illuminated by a laser light that is either monochromatic or quasimonochromatic. The lens following the transparency focuses the light at the Fourier transform plane. The second objective lens reconstructs the original transparency minus any information which had been removed by the spatial filter placed in the Fourier transform plane. The general optical system consists of a precise, shock absorbing, optical bench with mounts and holders allowing lens and filter changes as required. The choice of filters varies widely. Spatial filters take the form of circular aperatures, sector wedges, wires, or other empirically-determined shapes (see Figure A-5). If low spatial frequencies are to be eliminated at all orientations, the filter consists of an opaque disc. The cutoff frequency depends on the radius of the circle or disc. High frequencies can be removed by use of a standard photographic iris diaphragm. Wedge-shaped filters are used to remove lineations or striations.

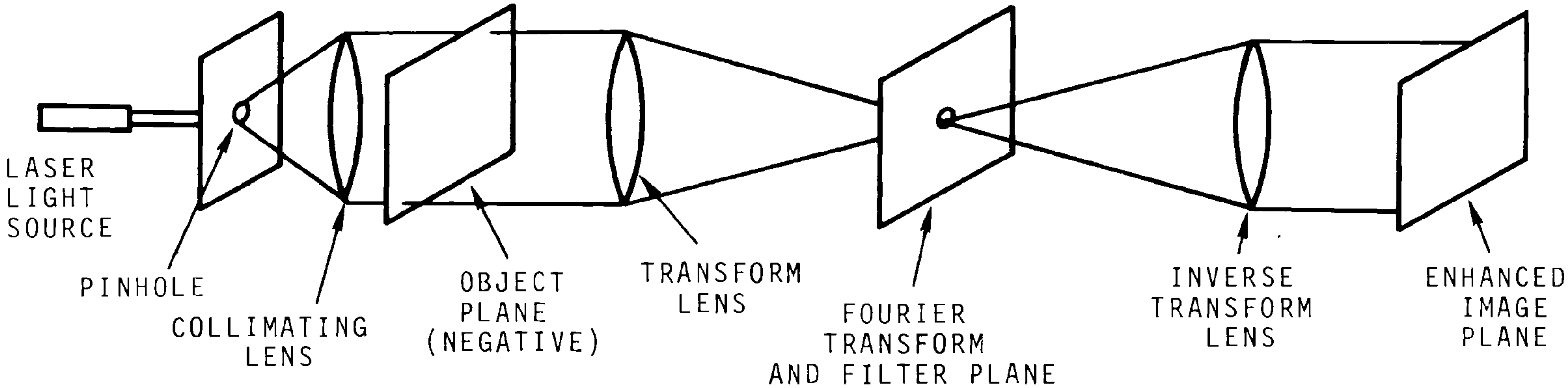


FIGURE A-4. TYPICAL COHERENT OPTICAL ENHANCEMENT SYSTEM

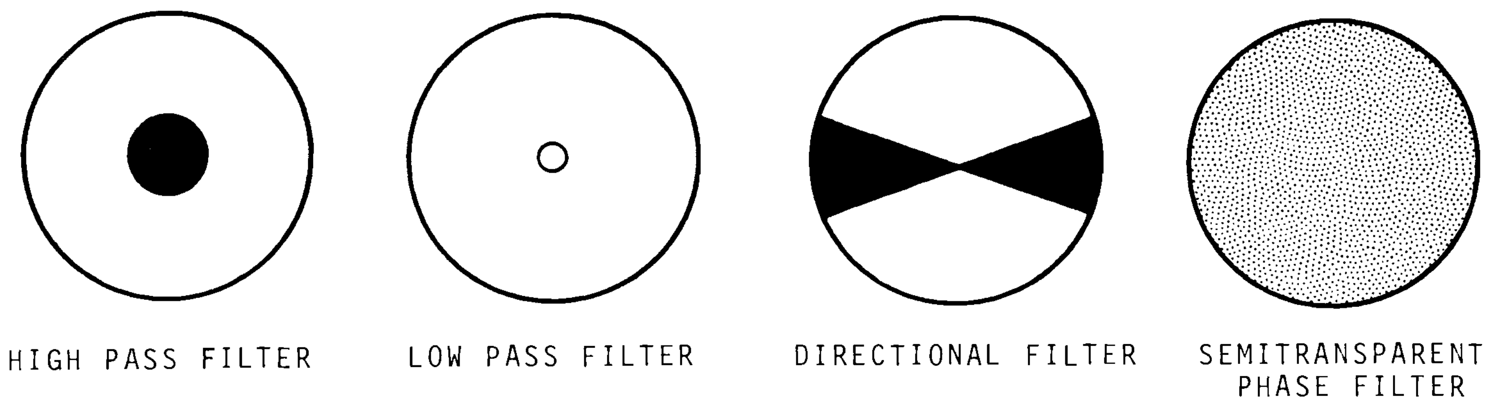


FIGURE A-5. TYPICAL FOURIER TRANSFORM PLANE FILTERS

The optical system is often used for pattern recognition. Thus predetermined patterns or geometric shapes such as chromosomes in biology, or ships or tanks in military intelligence, are pre-evaluated and placed on the filter. By comparing the known Fourier transform patterns for these shapes with the unknown transparency, one can determine the possible average distribution and density of the chromosomes or ships or tanks present in the pattern. Potential extension of this technique to homogeneity of UO_2+25 wt% PuO_2 sintered pellets, or voids in irradiated materials, is being studied. A typical commercial example of this coherent optical system is available from Conductron Corporation and is known as Laser Scan.* Thus the use of coherent optics, although still being developed, and only applied in a limited manner to materials technology, offers "real time" image enhancement capability. The main advantages of this system are its efficient storage of the large amount of data in a picture (the film is used as the storage) and the high processing speed due to the implicit parallel processing of all elements simultaneously. It has the disadvantages of being touchy to operate and therefore is subject to anomalies such as imperfect optical components, cleanliness, or alignment, and it has the inability to handle nonlinear problems (as compared to the computer). The suggested accuracy of the computer is $\sim$0.018%, while the best one can expect from a present coherent optical system is 3 to 5 percent.

Computer Method

One of the more recent developments in computer technology is picture or image processing. Advances in this domain have been rapid, prolific, and extremely useful. The most current

* Trademark of Conductron Corporation, Ann Arbor, Michigan.

examples are the computer enhancement of the Mariner, Ranger, and moon pictures from the NASA space programs. Actually, the computer can be used to enhance ordinary negatives or transparencies or can scan the image directly and convert the image to an electrical form. For the purposes of this discussion, the computer method of enhancement will use a negative as the original image form and direct conversion is considered an advanced technique and was discussed under that section of the report.

The computer process consists initially of scanning a negative or transparency.[15] Typical scanning equipment is a flying spot scanner. The resultant electrical signals from the scanner, representing the optical densities on the film, are changed into numerical representations on magnetic tape by an analog-to-digital converter. Typically there may be ∿500,000 samples for a 1 x 1-in. square transparency. This provides a digital version of the input picture for computer processing. Then, the operations that can be performed within the general purpose computer include smoothing, edge detection, correlation, pattern matching, distortion, filtering, addition and subtraction of gray tones, contrast sharpening, inversion of gray tones (black to white and vice versa). These computer manipulations can then be put on a CRT intermediate display console for interpretation and choice of final image. After the decisions of optimum image characteristics, the product of the computer operations is another digital tape containing the enhanced data, or, the data can be stored for later comparison with similar data. The final product is obtained from the high resolution image produced by the microfilm printer under computer tape control. This operation is an inverse of the original scanning operation. This typical process is illustrated in Figure A-6.

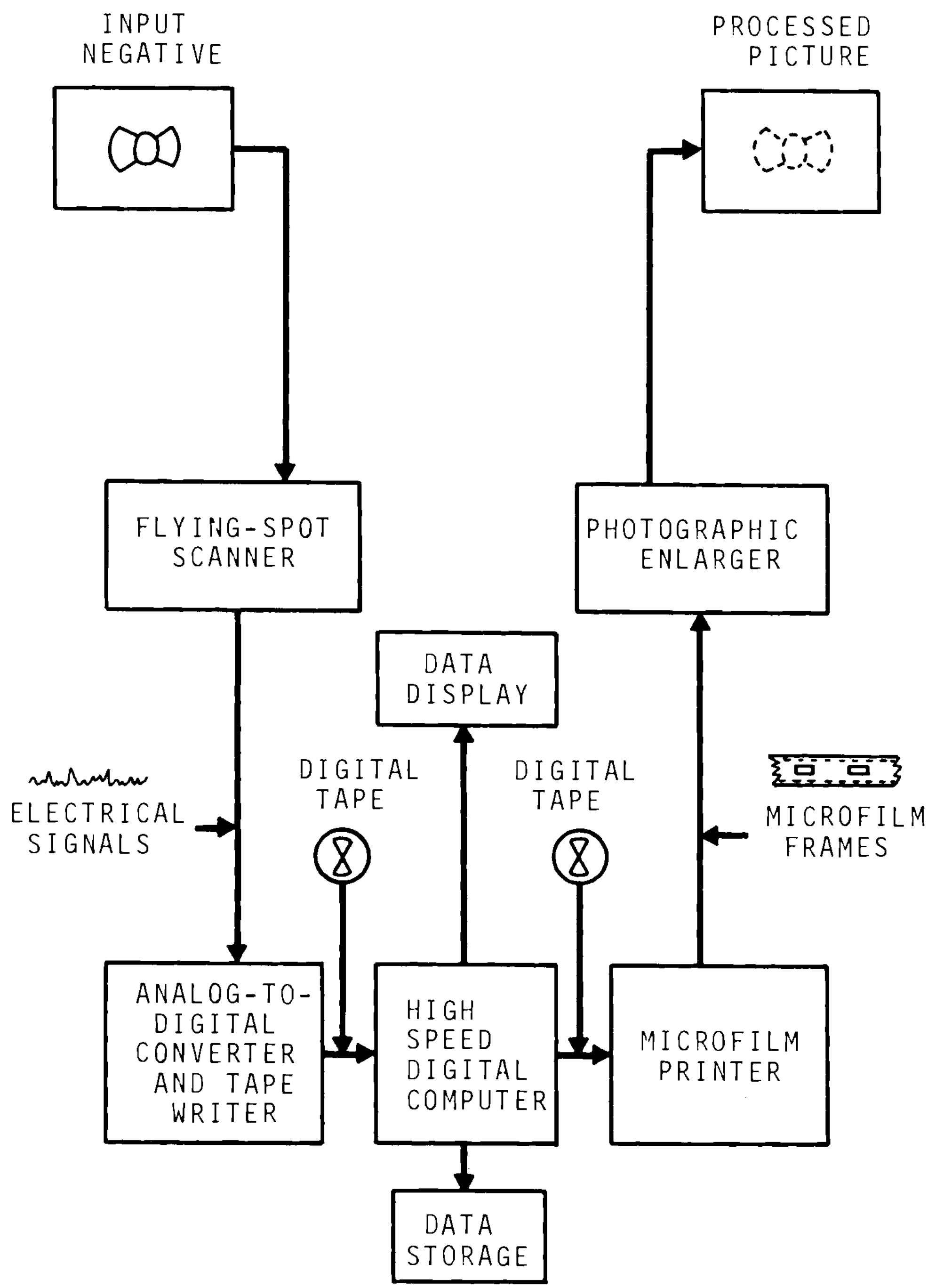


FIGURE A-6. TYPICAL COMPUTER IMAGE PROCESSING SYSTEM[7]

There are many variations on the input-output procedures and system mechanics. At the input, the picture can be specified by optical, mechanical, or electrical scanning or sensing devices. One of the main advantages of the computer system is the high degree of flexibility available in the computer over either the photographic or the optical method. For example, filtering of noise and undesirable matrix data. It should be noted that the gray scales mentioned in the photographic method are similarly a part of this method. In the initial scanning operation, the gray scales or densities are converted to numbers; e.g., low numbers represent low densities and high numbers represent high densities. The number of gray tone extractions is similar, in that 8, 16, 32, or 64 gray levels are used in the computer enhancement work.

One of the major factors involved in all of these enhancement techniques is resolution. In fact, the limiting factor in image processing is noise such as grain size on the negative or equipment noise in the system. It is a primary factor in the original choice of film. For instance, if coarse grain film is used there is little value in using an expensive, high resolution scanning device. However, recent techniques at Jet Propulsion Laboratory have illustrated means of minimizing the grain noise problem. Two, three, or more negatives are taken at the same time. These negatives are then image processed and the computer is capable of identifying minute differences between the silver iodide grains on each negative and through its high flexibility, the computer can subtract out the grain noise and in this way further enhance the results. The taking of three negatives is relatively cheap but must be considered at the exact time of picture taking as it cannot always be picked up at a subsequent time; e.g., neutronradiography of irradiated materials. Likewise, the resolution of the scanning device (beam spot size) must be strongly considered. High resolution scanners coupled with fine grained film will produce tremendous quantities of data. If these data are to be manipulated and possibly stored, the computer memory capability becomes a limiting factor.

Coordination and planning are a necessity in designing and using the optimum equipment in this image enhancement technique. It should be noted that due to this computer limitation, it is the usual practice to use only key parts of a negative rather than the entire negative, which is common in the photographic process. The application of computer image enhancement has been wide, with emphasis in the space, electronics, aerial photography for geological, agricultural and military intelligence, and medical fields, but noticeably lacking in materials development. The computer and associated equipment software development work has been extensive as noted by the depth of theoretical and engineering development activities in the literature.[1,2,8,16,17,18,19] Many current technical journals contain extensive instrumentation advertising that usually includes typical display methods for enhancing images.

The computer method of enhancement has a very high degree of flexibility in data manipulation, high cost, high volume, high accuracy, and is generally somewhat slow. It is trouble free once the system is in operation and can handle nonlinear problems. In practice, the accuracy of digital computer image processing is limited by the film scanner.

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