A real-time neutron radiography system has been developed at Oregon State University which is capable of producing neutron radiographs of objects and events concurrent with the incident radiation. The purpose of this thesis is to demonstrate the feasibility of the real-time technique as a further application of neutron radiography at OSU. The system has been used to demonstrate the application of real-time techniques to neutron radiography as a method of non-destructive testing. Results of this study showed that the system could produce images of static objects such as ammunition cartridges, and record the motion of the gas phase in two-phase systems.

General requirements for a real-time neutron radiography system are discussed, leading to the decisions made in choosing the components for the OSU
Real-Time System. Emphasis is placed on the illuminance from the light-producing elements of the system; a method of estimating this illuminance is presented. Procedures for evaluating the performance of the system are also explored.

The real-time system has undergone several alterations. Initially designed as a modification to the high-speed motion neutron radiography system, the real-time system uses a television camera to produce radiographic images. The best radiographs were produced using a reactor power level of 350 kilowatts and aligning the equipment so that the object or event maximized the viewing area of the television camera. Results also indicate a reactor power of one megawatt would help improve the resolution of the system.
Real-Time Neutron Radiography

by

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I. Introduction

1.1 Background

The concept of analyzing the interior of objects opaque to visible light is largely taken for granted today thanks to Roentgen's discovery of X-rays in 1895. Using neutrons to see through objects is not commonplace, however, largely because there are no strong, portable, and inexpensive neutron sources. Additionally, scientists have been aware of the penetrating ability of X-rays longer than they have known about the neutron's particular characteristics. Neutrons were discovered some forty years (Chadwick, 1932) after X-rays (1). Feasibility of a neutron radiography system was shown a few years after Chadwick's discovery by German scientists Kallman, Kuhn, and Peter (2,3) using small accelerator-type neutron generators. Although it was possible to produce an image using neutrons, the concept was not widely accepted primarily because accelerator sources yielded such low neutron fluxes. Kallman and Kuhn required a four-hour exposure from their source since it was so weak (2).
Potential neutron sources include generators, accelerators, isotopes, and atomic piles. Although early neutron radiographs were produced primarily with cyclotron generators, machines capable of large neutron fluxes were not plentiful. With the state of technology that existed in the 1930s the few high-flux generators built were used for higher priority research than neutron radiography. The advent of linear accelerators (late 1930s) was of limited usefulness due to low flux levels and inefficiencies in film radiography. Isotope neutron sources can be used for radiography, but only Californium-252 has sufficient flux levels to be seriously considered, and then only with high-gain image equipment or long exposure times. Reactors are by far the most plentiful source of neutrons, capable of easily producing fluxes many orders of magnitude greater than isotopes, accelerators, or generators (4).

The first radiograph taken with a reactor was in 1956 at Harwell, England by Thewlis and Derbyshire (3,5). Two of the first American neutron radiographs from reactors were produced in 1960 by Watts at the Armour Research Foundation and McGonnagle at Argonne National Laboratory (1). The importance of reactors to neutron radiography cannot be overstated; only a reactor can provide enough neutrons to penetrate most objects in
a reasonable time. Without reactors, neutron radiography might never have become a viable method of non-destructively examining the internal structure of objects.

Nuclear reactor design was not the only engineering field instrumental in the development of neutron radiography. In any radiographic process, radiation from the source must be recorded in some fashion so that the human eye can observe the image. Early radiographers used photographic film to capture images. With the electronic age, certain devices became available which could perform previously impossible functions, among which were amplifying and digitizing an electronic signal. Electronic equipment with similar capabilities has been used instead of photographic films to record the radiation image. Along with the increasing knowledge of nuclear phenomena, advances in imaging techniques have been indispensable in developing neutron radiography as an alternative method of non-destructive testing.
1.2 General Neutron Radiography

The discovery of radioactivity and subsequent application of atomic principles gave rise to a new science which became known as radiography. The term "radiography" can be used to describe any system that uses radiation to penetrate an object and produce an image of modulated radiation after passing through the object. Figure 1.1 shows a uniform radiation beam passing through an object which modulates the beam spatially as the beam passes through different components of the object. Every material has a different interaction probability and it is the difference in these interaction probabilities that spatially changes the incident beam. The modulated beam then crosses the image plane: a plane behind the object and perpendicular to the beam line where the image is recorded.

Differentiation between the various types of radiography is based on two factors: type of radiation and method of imaging. Most radiography is performed with either X-rays or neutrons (gamma rays are suitable and behave similarly to X-rays). X-rays and neutrons are clearly different forms of radiation; hence they interact differently with any given compound or element. As ionizing electromagnetic radiation, X-rays interact
Figure 1.1
General Radiographic Process
with the electron cloud of atoms. As the atomic number increases, so does the size of the atom and its electron cloud, increasing the probability of a radiation-matter interaction. The interaction probability can also be affected by the distance radiation travels through the object (i.e., target thickness). A greater target thickness increases the probability of interaction since there are more atoms present for the radiation to react with. This probability of interaction is called the mass absorption or mass attenuation coefficient. Included in the mass absorption coefficient is a relationship between target thickness and radiation-matter reactions, making it convenient to compare interaction probabilities of different elements as a function of atomic number. As shown in Figure 1.2, the mass absorption coefficient for X-rays increases almost linearly as a function of atomic number. This is in definite contrast to the mass absorption spectrum for neutrons, also shown in Figure 1.2. The primary reason is that neutron interactions are dependent on nuclear forces only (rather than the size of the electron cloud). These nuclear forces, still largely mysterious in their nature, control the probabilities for the various types of scattering and absorption reactions. The probability of neutron interaction depends on
Figure 1.2
Comparison of Thermal Neutron and X-ray Mass Attenuation Coefficients
factors such as atomic number, neutron energy, neutron/proton ratio, and other atomic and quantum mechanical phenomena; it is therefore hardly surprising that the mass absorption coefficient is not a smooth function of atomic number but rather an apparently random variation between the elements.

The second distinguishing feature of a given radiography system is the mechanism by which the image is transformed from non-visible radiation into a picture visible to the human eye. There are several ways to produce an image in a radiographic process; however, almost every method uses some type of photographic film for the final result. For example, the following sequence of events is required to produce a neutron image on film using a stationary object and constant source strength. A uniform beam of neutrons strikes the object, which absorbs some particles and causes others to scatter, thus diverting some number of neutrons from their original paths. Under the new spatial orientation, the neutron beam crosses the image plane, where a light-tight container holds film and a converter foil in contact (the light-tight container is called a cassette, and is made of a material transparent to the incident radiation, in this case aluminum). Neutrons pass through the film with almost no effect and strike the converter
foil, producing secondary radiation from the foil surface next to the film. The secondary radiation exposes the film, and since the foil touches the film, virtually no distortion occurs. The film is then removed (avoiding exposure to other light sources) and developed according to film type, usually in a standard black-and-white processing scheme (developer, stop bath, and fixer). This example describes a common radiographic procedure called "static" radiography and is illustrated in Figure 1.3a. Static radiographs provide a straightforward approach to the problem of changing invisible radiation into a visible image.

Another mechanism for transforming the neutron signal into the visible spectrum is scintillation, which is compared to the static technique in Figure 1.3b. Like converter foils, scintillators absorb neutrons and emit secondary radiation. The steps needed to obtain a visible image via scintillation are slightly more complicated than the static procedure described above. As in static radiography, a neutron beam is spatially modulated by passing through an object. Upon crossing the image plane, neutrons interact with a scintillator, which absorbs neutrons and emits visible light. Scintillator light is very faint and needs amplification by an electronic image intensifier of some kind. After
Figure 1.3
Comparison of Static, Scintillation, and Real-Time Techniques
amplification several options present themselves for recording the visible image. Perhaps simplest of all would be a standard 35mm camera used for still photography. The camera would be focused on the output end of the intensifier and triggered remotely when neutrons activated the scintillator, thus producing a static radiograph via scintillation rather than converter foil. Static and dynamic events can be radiographed using a motion picture camera instead of a 35mm camera. The camera (focused on the image intensifier) would be triggered to coincide with an event and the incident radiation. In either case, the film would then be processed appropriately. Dynamic events can be radiographed by other means: if a closed-circuit television camera replaces the motion picture camera, the dynamic event becomes visible immediately. This entire process, from neutron beam to television image, is called "real-time" neutron radiography (see Figure 1.3c). The conceptual difference is that "real-time" objects are viewed concurrently with the irradiation whereas "film" objects are viewed after irradiation and development of the film. The physical difference is the use of either a television camera or a fluorescent screen instead of photographic film.
1.3 Historical Review of Real-Time Radiography

The history of real-time radiography dates back to the turn of the century under the name of fluoroscopy. As early as 1897 customs officials used fluoroscopes for inspecting luggage at European railroad stations. In a fluoroscope, penetrating X-rays display images on a phosphor screen. Some phosphors developed for fluoroscopy include barium platinocyanide and cadmium zinc sulfide (6). The function of the phosphor screen is to absorb radiation and emit secondary radiation in the visible spectrum. This step of absorption and secondary emission is essential in both X-ray and neutron radiography.

Real-time neutron radiography is much more recent. Before a real-time neutron system could be realized, advances in neutron source and image technologies were necessary. Perhaps coincidentally, nuclear reactor designs were maturing around the same period as certain electronic equipment became feasible. Innovations in different fields from the early 1950s to the mid 1960s produced two devices that, when used in conjunction with each other, constituted a real-time neutron imaging system: a thermal neutron image intensifier and a highly sensitive television camera. "Thermal" is a term used to
describe neutrons in the energy range of zero to one electron-volt. It should be noted that the thermal neutron image intensifier does not amplify or intensify the neutrons; rather, the neutron image is transformed into visible light which is then electronically amplified. Neutron image intensifiers follow the design of X-ray image intensifiers as can be seen by comparing Figures 1.4 and 1.5. Both types of intensifier tubes have a photoemissive detection layer and use an electronic potential to drive the image from input to output. X-ray image intensifier tubes have been used in radiographic applications since the early 1950s (6), but it was not until 1966 that Berger produced the first successful real-time neutron radiography system using a neutron sensitive intensifier tube (7). Figure 1.4 shows the intensifier: an evacuated glass envelope coated with a mixture of zinc cadmium sulfide(Ag) phosphor and Lithium-6 enriched (95.72 % enrichment) lithium fluoride provides a photoemissive surface to convert the neutron signal into light. Note that this photoemissive surface is analogous to phosphors used in fluoroscopy and recall that the mechanism is called scintillation in neutron radiography.

The intensifier developed by Berger, et. al. (Figure 1.4) was specifically designed to interface
Figure 1.4

Berger's Thermal Neutron Image Intensifier Tube
Figure 1.5

Diagrams of (a) Westinghouse Fluorex and (b) Philips X-ray sensitive image intensifiers
with the second major innovation in real-time neutron technology: a low-light-level television camera tube called the Secondary Electron Conduction (SEC) Vidicon. While the invention of the SEC camera was not directly initiated by interest in neutron radiography, certain characteristics of the new design were found quite useful in producing an image from neutrons. Of prime importance was the camera's ability to integrate weak signals to produce a daylight quality single frame image. Additionally, the SEC Vidicon was nearly one thousand times more sensitive than common photographic film (4). For real-time radiography this meant lower neutron source fluxes would be needed for an image.

The system Berger used in developing his thermal neutron image intensifier employed the Juggernaut reactor at Argonne National Laboratory. Berger reported good image quality for fluxes on the order of $10^7$ neutrons/sq.cm.-second, and detectable images as low as $10^4$ neutrons/sq.cm.-second. Output from the intensifier varied linearly with incident thermal neutron beam flux: a beam of $10^4$ neutrons/sq.cm.-second produced approximately 0.01 of a footcandle while a beam of $2.6 \times 10^7$ neutrons/sq.cm.-second produced over twenty footcandles of light (8). With neutron radiographs possible at such low flux levels, experimenters became
aware that sources other than nuclear reactors might be used for real-time neutron radiography. The key to producing these radiographs seemed to be the coupling of a neutron sensitive image intensifier with a television camera sensitive to low light levels. In the early 1970s, National Aeronautics and Space Administration (NASA) scientists Beal and Brown developed a real-time neutron radiography system at Marshall Space Flight Center (MSFC) using a Van de Graaff accelerator, scintillator, image intensifier, and SEC vidicon television camera. With fluxes ranging from $10^3$ to $10^7$ neutrons/sq.cm.-second the NASA system could image ordnance hardware, hydrogen contamination in titanium welds, and other items where non-destructive testing was needed to assure functioning equipment for spacecraft (4). Other examples of non-reactor real-time neutron radiography systems include:

1) Shaw, Cason, 1971 (9)  
Sponsor: Westinghouse Electric Co.  
Source: Californium-252  
Flux: $10^6$ neutrons/sq.cm.-second

2) Wilson, Hildreth, Fussa, 1971 (10)  
Sponsor: High Voltage Engineering Corp.  
Source: Van de Graaff generator  
Flux: $10^6$ neutrons/sq.cm.-second
3) Kawasaki, 1968 (11)
Sponsor: Toshiba Electric Co., Japan
Source: Accelerator
Flux: $10^4$ neutrons/sq.cm.-second

4) Panhuisie, 1980 (12)
Sponsor: University of Missouri
Source: Californium-252

While non-reactor sources are attractive due to their affordability and portability, reactors still possess many advantages, most of which are directly or indirectly related to high neutron fluxes. Often the decision concerning which source to use for radiography is a function of economics and/or availability. NASA's real-time radiography unit at MSFC uses a Van de Graaff accelerator because they already had the machine and estimated it less expensive to develop an improved imaging system rather than purchase or build a nuclear reactor. Hendry, et. al. (13,14) made a similar decision when building a real-time system in 1968 for the United Kingdom Atomic Energy Reactor Group in Scotland, except that they already had a reactor. The imaging equipment chosen was a separate scintillator and image intensifier instead of the combined tube of Berger's design since:

"...it seemed more important at the time to set up a system capable of utilizing standard intensifiers (which still seemed to have a considerable potential for further development) rather than have a neutron sensitive device developed for this one application" (13).
The separation of scintillating material and image amplification is more common in recent real-time systems since it allows flexibility in the use of the imaging equipment (for example, variation of scintillator components or intensification of images from radiation other than neutrons). Examples of other reactor-source real-time radiography units are:

1) Berzins, 1978 (15)
   Sponsor: Los Alamos National Laboratory
   Flux: $4 \times 10^7$ neutrons/sq.cm.-second

2) Matsumoto, 1981 (16)
   Sponsor: Nagoya University, Japan
   Flux: $10^6$ neutrons/sq.cm.-second

3) Stewart, 1981 (17,18)
   Sponsor: Rolls-Royce Limited, England
   Flux: $2-3 \times 10^5$ neutrons/sq.cm.-second

4) Fujine, 1983 (19)
   Sponsor: Kyoto University, Japan
   Flux: $10^6$ neutrons/sq.cm.-second

5) Davis, 1982 (20)
   Sponsor: Georgia Institute of Technology

6) Bryant, 1983 (21)
   Sponsor: Los Alamos National Laboratory

Further modification of Berger's first real-time system became possible with advances in computer technology. Using digital techniques, an image may be broken down into small pieces or pixels, stored in a
computer, and be processed to enhance, define, add color, or be manipulated in other ways. An example of video processing is the system built by Neelakantan and Subramanian using a microcomputer to enhance edges in neutron radiography images (22). NASA scientists at Lewis Research Center led by Vary developed a computer enhancer for radiographs (23,24); Brown at MSFC also used digital methods to integrate images for a more defined radiograph (25).
1.4 Radiography at OSU

Many types of film radiography have been performed at Oregon State University using the Oregon State TRIGA Reactor (OSTR), including static, pulsed, and high-speed motion neutron radiography (26,27,31,32,33,34). Static radiography involves a stationary object and constant radiation source strength. Pulsed radiography uses a radiation source that can achieve high power levels very quickly and for very short periods (a common OSTR pulse has a peak power of 3000 megawatts and a full-width-at-half-maximum, or FWHM, of eight milliseconds). In either pulsed or static radiography the image is recorded by some type of converter foil which, after absorbing a neutron, emits a particle which will expose the film (conversion of the neutron is necessary because neutron sensitive film does not currently exist). The major difference between these two types of radiography is the source: pulsed radiographs result from a burst of neutrons where power varies with time; static radiographs result from exposure to a constant source power over time. High-speed motion neutron radiographs have been produced with the OSTR in pulse mode using the scintillation technique in place of a converter foil and a HYCAM 16mm high-speed camera to
capture the image on film. Figure 1.6 illustrates each process, and a more complete description can be found in reference (26) or section 1.2.

The real-time imaging system developed at OSU is a modification of the high-speed imaging system already in use. For real-time, the 16mm high-speed camera is replaced with a television camera -- not an ordinary television camera, but one sensitive to very low light levels. Additionally, the camera must be sensitive to the particular spectral output of the scintillator: it would be most ineffective for the camera to be tuned toward red when the scintillator emits green or blue light. In following the path of the neutron image through the real-time system, the modulated neutron beam is transformed into visible light (wavelength of 4500 Angstroms, in the blue-green region) by the scintillator, which is then amplified by the image intensifier, received by the television camera, and finally transferred through a television cable to a viewing screen outside the shielding where the image can be seen by the human eye. Hence, real-time radiography can be viewed concurrently with the irradiation while film radiography cannot be viewed until after the film is developed, a process taking from thirty minutes to a few hours. Of course, there is a time lag in the
Comparison of Static, Pulsed, and High-Speed Neutron Radiography

Figure 1.6

Comparison of Static, Pulsed, and High-Speed Neutron Radiography
real-time process since light travels at a finite speed, but it is hardly comparable to the time lag involved with film radiography.

At this point one drawback of a real-time system could be the lack of a permanent record of the radiograph as found in a film system. However, with a video recorder it is simple to record the radiograph while viewing it by connecting the recorder into the monitor on which the image is seen. Figure 1.7 shows the imaging equipment outside Beam Port #3: a black-and-white television monitor and a video-cassette recorder. The video image can also be photographed if desired for a more tangible result. Unfortunately photographs do not always reproduce the video image in perfect form due to some inherent problems (see Figures 3.3 and 3.4). Nevertheless, photographs still complement the system by providing a "hard copy" result.
Figure 1.7

Imaging Equipment Outside Beam Port #3
II. System Requirements

2.1 Characteristics of a Real-Time Neutron Radiography System

Common to any radiographic system are four components: a radiation source, a collimator, an imaging process, and appropriate shielding. The real-time neutron radiography system developed at OSU uses a TRIGA Mark II (built by General Atomic) with Fuel Lifetime Improvement Program (FLIP) fuel (70% enriched Uranium-235 in zirconium hydride) -- a highly versatile research reactor. The advantages of using a reactor are manyfold, including:

1) Reactors are very prolific sources of neutrons, even at low power levels.
2) Most reactor beams are rich in thermal neutrons compared to other sources.
3) Most applications allow the inspection objects to be taken to the source rather than requiring the source be taken to the object (28).

By far the greatest advantage of reactors is source strength. Most reactors can operate at various power
levels and some, like the OSTR, can be pulsed for a very intense neutron beam over a few milliseconds. Unfortunately for radiography, reactors do not emit thermal neutrons in parallel beams immediately upon fission. Rather, neutrons are emitted isotropically (in all directions) at energies in the mega-electron-volt range. Therefore, neutrons from a reactor must be slowed down to thermal energies (around 0.025 electron-volt) and then collimated into a parallel beam. Thermal neutrons are not the only type used in radiography, but the thermal energy range exhibits the most interesting and useful attenuation characteristics, and thermal neutron images are the easiest to detect and record (28).

The process for slowing down neutrons is called moderation, and takes place in a material called the moderator, an element of low atomic number (usually twelve or less) which can absorb much of the neutron's energy in billiard-ball type collisions. After being born in fission, high-energy neutrons collide with the atoms of the moderator until the neutrons have lost much of their original energy and changed direction many times. Once the neutron has been slowed down to the thermal range it can be used in radiography; however, the thermal neutrons are isotropic and cannot produce
the resolution or clarity of a parallel beam. Since neutrons have no charge they cannot be diverted by a magnetic field like the charged particles in an accelerator. In fact, the process by which a neutron beam is obtained is nearly opposite the idea behind accelerators: instead of forcing the particles into travelling a certain direction, all neutrons not travelling a certain direction are blocked out. Collimation is the term used to describe masking diverging particles so that a parallel beam remains.

A typical collimator is a long tube with one end aimed toward the source and the other toward the object, providing a straight line between the two (as an example see Figure 2.1, an illustration of the collimator used in Beam Port #3, an OSTR beam port used for radiography). Inside the tube are holes and/or slits which block diverging neutrons. The end of the collimator pointed toward the reactor sees a broad surface of moderator with mostly thermal neutrons diffusing in all directions. Only the neutrons travelling in the desired direction will traverse the length of the collimator to be used in a radiograph. In practice, a perfectly parallel neutron beam is very difficult to achieve and results in low flux levels -- fewer neutrons to radiograph with. Hence, a slightly
Figure 2.1
Beam Port #3 Collimator
divergent beam is often used since it has most of the advantages of a parallel beam (primarily resolution) without sacrificing intensity (29). Obviously, too divergent a beam would result in much the same situation as if no collimator were used at all: poor resolution from large scattering angles.

Collimators are usually described in terms of their length-to-diameter (L/D) ratio. Length is the distance from source to object; diameter is the smallest opening particles must pass through in travelling the length of the collimator. As length increases, more unwanted particles are masked out since the object is farther away from the source. As diameter decreases, particles must travel a more parallel path to reach the object. Collimators select neutrons travelling only in a certain solid angle to produce a neutron beam; the L/D ratio determines the angular divergence of that beam. For example, suppose a radiographer wants to image an object with a thickness step change from t to T. The error induced by non-parallel particles produces a band where a sharp step change should be. This L/D effect on the resolution of an edge can be seen in Figure 2.2. If resolution were top priority, a high L/D would be required. However, resolution is not free: better clarity costs beam intensity. In fact, the neutron
Figure 2.2

L/D Resolution Effect

(a) Large L/D Resolution Effect.

(b) Small L/D Resolution Effect.
flux, $\Phi$, is proportional to the inverse of the square of the L/D ratio:

$$\Phi \propto 1/(L/D)^2 \quad \text{(Eqn. 2.1)}$$

Thus, increasing L/D by a factor of ten will decrease the flux at the object by a factor of one hundred. Cutforth recommends a L/D of 50:1 for most applications, and a minimum of 10:1 for useful resolution (28). The collimator used in the OSU Real-Time Neutron Radiography System has a L/D of approximately 30:1, allowing for good resolution while preserving sufficient flux at the object.

Having described the first two components of the radiographic system (the source and collimation), it is time to consider the third component: the imaging process. Neutrons, largely because they are uncharged, are difficult particles to record directly by any method known today. In any process for producing a neutron image the neutrons must first interact with a substance that can transform the image in some fashion so that it can be recorded. In a real-time system the modulated neutron beam is transformed to visible light by a scintillator.

Scintillators are composed of two major constituents. First is some material with a high cross section for neutron absorption which emits ionizing
radiation after absorbing a neutron. Second is a scintillation material -- a substance that emits light when excited by ionizing radiation (27). The materials are held together by a binding compound and placed on a substance relatively transparent to neutrons such as aluminum. This combination of absorber, emitter, binder, and backing is called a scintillator screen. Compared to other imaging techniques, scintillator screens are capable of producing an image with the least neutron exposure. Also, changing the image from neutrons to visible light makes it possible to manipulate the beam with familiar methods. For example, the image can be amplified, and more directly applicable to real-time neutron radiography, the image can be seen by a television camera.

The next step in real-time imaging is the television system -- camera, monitor, and electronic coupling. The most crucial part is the camera since it must be able to detect light from the scintillator. Television is quite well suited for this task, especially considering its purpose according to D. G. Fink: "The fundamental aim of a television system is to extend the sense of sight beyond its natural limits" (30).

Actually, the human eye could possibly see the
light from the scintillator directly; however, the environment would be very unnatural and quite harmful due to the neutron beam. It is because of this hazardous environment that the final component of the entire system, biological shielding, is required, as well as a method of bringing the neutron image from the beam area to a safe place outside the shielding.
2.2 Decisions Made in Choosing Components for the OSU Real-Time Neutron Radiography System

Decisions regarding the radiation source used in the OSU Real-Time Neutron Radiography System were relatively simple in light of previous work done at OSU. In view of the advantages of reactors mentioned earlier (as well as prior experience and reactor availability) it made sense to choose the OSTR as the source. The OSTR has four beam ports where radiography could be performed (35). Presently only two are in use: Beam Port #1 for static and Beam Port #3 for high-speed radiography. Beam Port #3 (see Figure 2.3) was chosen for the collimation component of the real-time system because of previous experience in high-speed radiography and because only Beam Port #3 has shielding large enough to allow workers inside to situate the imaging equipment. In addition, the axis of Beam Port #3 is positioned tangentially to the reactor core so that very few gamma rays can escape down the beam tube, thus reducing false images caused by stray gammas. Choice of the scintillator was based on work by R. H. Bossi (27) who found a lithium fluoride/zinc sulfide mixture the optimum combination for high-speed radiography at OSU. While a scintillator for high-speed radiography may not be the optimum choice
Figure 2.3
Configuration of the OSTR Neutron Beam Ports
for real-time because of the spectral differences in sensitivity between high-speed film and television imaging, it seemed logical to begin experimenting with a previously tested scintillator. Choosing the final part of the system, the television camera, was not as easy as choosing the rest of the system, however.

The single most difficult question to answer about the television camera was this: How sensitive must the camera be to detect the light from the scintillator? (i.e., How much light does the scintillator emit?)

Camera sensitivity is measured in units of "foot-candles", defined as one lumen per square foot, or "lux", defined as one lumen per square meter (i.e., luminous flux per unit area or illumination). Thus, by definition, one footcandle equals 10.76 lux. A lumen is defined as "the visible energy radiated by a point source of one candle within a unit solid angle (1/4\pi of a sphere)" (30). Therefore, a point source of one candle emits 4\pi lumens. Originally, the candle was defined as the light from a tallow candle under certain specific conditions (composition, burning rate, size). Currently, one candle is 1/60 the rate which visible energy radiates from one square centimeter of a black body at 2045 degrees Kelvin, the temperature where platinum freezes. Clearly, the footcandle is not an easy
dimension to grasp intuitively like feet or gallons. However, consider these examples from the CRC Chemistry and Physics Handbook, sixty-third edition:

"Full sunlight with zenith sun produces an illuminance of the order of 10,000 footcandles on a horizontal surface at the earth's surface. Full moonlight provides an illuminance of only about 0.02 footcandle also at the earth's surface. Adequate illumination for steady reading is taken to be about 10 footcandles; that for close machine work is about 30 to 40 footcandles" (36).

In view of the above comparisons perhaps the original question of sensitivity can be rephrased: Which does the scintillator light most resemble -- full sunlight, full moonlight, reading light, or machining light? While it has not been tried, it is doubtful a person could read in Beam Port #3 from the scintillator emission. The illumination is probably considerably less than ten footcandles and more on the order of moonlight (i.e., less than one footcandle). Nonetheless, a more trustworthy estimate would be useful.
2.3 Illumination Estimate

In an effort to achieve a more accurate estimate, an experiment was performed to measure the light output from the image intensifier and scintillator. It was theorized that a very fast photographic film could record the light output from the intensifier and possibly the scintillator alone if the shutter was open for a long enough period. Densitometer readings, together with the characteristic curve of the film supplied by the manufacturer, should be sufficient to estimate the light output in lux (or footcandles) of the image intensifier and/or scintillator. The film chosen was FUJICOLOR HR1600 because it is one of the fastest films readily available. By comparison, film used for daylight photography is commonly ASA 64, whereas this film is ASA 1600 (ASA is a term used to describe the speed of film; a large ASA means the film is very fast and can record images with very little light).

Imaging components were arranged as shown in Figure 2.4, including a 35mm camera positioned in the beam to record the light output. A twenty-foot cable attached to the shutter release allowed operation of the camera from outside the beam port. With the reactor at thirty-five kilowatts and the camera F-stop constant at 1.4, several
Figure 2.4
Configuration of Imaging Equipment for Scintillator Light Measurement
frames were exposed at periods varying from 1/2 second to fifty seconds with the image intensifier and one second to seventy-five seconds without the intensifier. The developed negatives showed images at exposures greater than 1/2 second with the image intensifier, and at exposures greater than fifteen seconds with the scintillator alone. Density readings were compared to the exposure times in seconds, and a graph showing the relationship is presented in Figure 2.5. Note that the exposure having the greatest film density was fifty seconds with the image intensifier, giving a maximum density reading of 1.6.

To estimate the illumination it is necessary to consult the characteristic curve of FUJICOLOR HR1600, shown in Figure 2.6. A density of 1.6 relates to a value of -2.0 (estimating the intersection of 1.6 and some point between green and blue since the graph does not show exactly a wavelength of 4500 Angstroms). To find lux one must take the inverse log and divide by the shutter speed, in this case 1/125 of a second (see upper left hand corner of Figure 2.6). The calculation shows that an estimated illuminance of 1.25 lux (0.125 footcandle) is present at thirty-five kilowatts from the scintillator/image intensifier combination. This is an estimate of the maximum illumination at thirty-five
DENSITY MEASUREMENTS
TAKEN FROM FUJICOLOR
HR 1600 FILM

Figure 2.5
Comparison of Film Density to Exposure
Figure 2.6

Characteristic Curve for FUJICOLOR HR1600

EXPOSURE: DAYLIGHT 1/125 SEC
PROCESS: CN 16
DENSITOMETRY: STATUS M

EXPOSURE [LOG H (LUX-SECONDS)]
kilowatts since the density reading originated from the darkest image.

There is evidence that the estimate is reasonable. First, the calculated illuminance is close to the original estimate discussed in section 2.2. Second, section 1.3 discussed an early intensifier (8) with illuminance ranging from 0.01 to twenty footcandles. Since there exists a common denominator between these two experiments (i.e., neutron exposure is the driving force behind the light emission), flux levels can be directly compared with other systems because flux is an independent quantity relative to any system. Flux in Beam Port #3 has been determined to be $5.09 \times 10^6$ neutrons/sq.cm.-second at thirty-five kilowatts (37). Comparing flux levels reported in section 1.3 and the current discussion, 1.25 lux is within the range of observed illumination of the early intensifier at similar fluxes. This is very convincing, and might lead to an assumption that the estimate is completely valid, but some irregularities are evident in making the above estimate.

First, there is no reference to the F-stop used to produce the characteristic curve in any of the information supplied by the film's manufacturer. Second, shutter speeds used to estimate the imaging equipment's
light output (Figure 2.5) vary by several orders of magnitude compared to the exposure time used to create Figure 2.6. If the shutter speed and F-stop positions were constant between the experimental measurement and characteristic curve, a direct correlation could be made; however, the exposure periods are not constant, and a direct relationship is highly suspect of error, especially when the F-stop used in Figure 2.6 is totally unknown. Third, the film data sheet mentions that FUJICOLOR HR1600 is extremely sensitive to radiation damage. This is not altogether surprising, and became obvious when examining the film because it was completely darkened even in areas around the sprocket holes and between picture frames where no light should reach. Background density measurements in these areas produced values of approximately 1.1. Assuming gamma radiation has somehow affected the film density measurements, a possible method to account for this extra exposure is to subtract the background from the density reading: if the background is removed from the 1.6 measurement, a density value of 0.5 results. Comparing this value with Figure 2.6 shows that 0.5 does not intersect any part of the blue or green spectrum; since the scintillator's light output is definitely in this range, background subtraction is apparently an
incorrect method of accounting for the extra radiation. Moreover, because the background cannot be directly removed, it is possible that the superfluous gamma radiation did not adversely affect the film density with respect to light of a blue or green color (specifically 4500 Angstroms).

The purpose of exploring these irregularities is to determine if the estimated illuminance of 1.25 lux is valid or if a correction factor need be applied. Unknown are the F-stop relative to the manufacturer's data in Figure 2.6, the effects of different shutter speeds, and the effect of gamma radiation on the film density. However, one fact can be found which will help to decide if an adjustment to the estimate is necessary. If a television camera of known sensitivity were placed in the beam to detect any light emission, a minimum illuminance could be determined for the scintillator/image intensifier since television units have a minimum required light level for usable pictures. To this end, a standard television camera (sensitivity of nine footcandles, common to many home video systems) was placed in Beam Port #3 as the final step in the radiographic process.

The reactor was brought critical, the collimator was opened, and neutrons were allowed to strike the
scintillator. In this experiment an image intensifier (used extensively in the high-speed system) was used to boost the scintillator light on the premise that if a standard home video camera could detect anything at all it could detect amplified light rather than scintillator emission alone. To reduce the radiation exposure to the camera a mirror was placed behind the image intensifier at a forty-five-degree angle to the beam (see Figure 2.7) since it was thought that neutron radiation could damage the camera's lens by turning it opaque to visible light. In an effort to optimize the standard camera's chance of success, no object was placed in the beam so that the maximum number of neutrons would strike the scintillator; only a cadmium mask with a rectangular hole (1/2 by one inch) stood between the beam exit in the shielding and the scintillator. If the camera was able to detect the unperturbed amplified signal in the shape of the rectangle, then at least nine footcandles of light must have been given off at the intensifier output.

The experiment resulted in detection of the beam by the standard television camera. This proved the feasibility of a real-time system at OSU and demonstrated that sufficient light was given off by the scintillator and image intensifier for detection by
Figure 2.7
Schematic Plan of Imaging Equipment
Inside Beam Port #3
a television camera of only normal sensitivity. Moreover, at least nine footcandles (100 lux) is produced by the image intensifier at thirty-five kilowatts since the standard video camera was able to detect the rectangular hole in the cadmium mask. This evidence contradicts the illumination estimate of 1.25 lux, and implies the estimate is conservative by as much as two orders of magnitude.

Although there is an indication of significant error in the estimated illuminance, it is realistic that the estimation is not precisely correct in light of the unknown factors involving shutter speeds, F-stops, and gamma-caused background exposure. Further, note that the apparent error is such that the estimate is certainly less than the actual illuminance. This relationship brings to mind a fourth irregularity, leading to a possible explanation. Consider again Figure 2.5, and observe that the density readings never achieve a constant maximum level for different exposures, possibly implying that the shutter was never open long enough to record the total light output from the image intensifier. If this were the case, then the density readings would show some fraction less than the total illuminance, a condition possibly illustrated by the discrepancy between the estimated illuminance (1.25 lux)
and the minimum light required for the standard video camera (100 lux). While it is conceivable that the error in estimated light output is due entirely to this effect, it is more likely that a combination of all four unknown quantities has influenced the illumination estimate, although failure to achieve a constant maximum film density may be the dominant effect. Nevertheless, the estimate has some validity from comparison with Berger's thermal neutron image intensifier (section 1.3). Given an understanding of the irregularities involved, it seems reasonable to accept the 1.25 lux estimate under the qualifying restrictions that a) 1.25 lux is an underestimation, and b) the estimate may be conservative by as much as two orders of magnitude.
2.4 Choosing the Television System

Armed with a qualified illumination estimate, the search for a specific television camera began. The first criterion the camera had to meet was better sensitivity than the standard (i.e., able to produce an image using less than nine footcandles of light). A question may be raised here as to why a more sensitive camera was needed when a functioning camera had already been found. First, the standard camera was not available for radiography on a permanent basis. Second, any object in the beam will decrease the number of neutrons striking the scintillator. For example, a steel block 3/4 inch thick will decrease beam intensity at the scintillator by approximately a factor of ten. To compensate, either neutron flux or television sensitivity must increase by at least that amount to obtain the same image quality as previously. Third, increased camera sensitivity would allow lower neutron flux levels to give an acceptable image, decreasing radiation exposure and contamination to the imaging equipment -- primarily the camera and image intensifier. Moreover, if the camera was sensitive enough, the image intensifier might be omitted altogether. Contrast and resolution characteristics might also be improved with a highly sensitive
television camera, and as a further application, conceivably a portable system based on Californium-252 as a neutron source could be considered. Lastly, lower fluxes would mean less handling problems for objects radiographed since they would be exposed to less radiation (20).

The sensitivity of a television camera is largely dependent on the photoconductive material used in the television tube inside the camera. In darkness the photoconductor acts as an insulator; when light strikes the photoconductor, its resistance decreases, causing the lighted area to become positively charged. The scanning electron beam inside the television tube deposits electrons on positively charged areas, inducing current pulses which constitute the picture signal. Sensitivity is thus a function of two variables: the amount of light required to decrease the photoconductor's resistance and the magnitude of the current pulse necessary to create a signal. Additionally, the light incident on the photoconductor must be of the correct wavelength. As noted in section 1.4, the scintillator used in the high-speed imaging system emits secondary radiation in the blue-green part of the visible spectrum. Therefore, the camera used for real-time had to detect not only images under one
footcandle but also images composed of blue-green light. This required spectral response posed no overwhelming difficulty; however, it is worth noting that the television camera industry seems to produce low-light cameras sensitive toward the red and infrared more than any other wavelength primarily due to military and security applications regarding personnel detection devices for use at night or in lightless environments.

The second criterion the camera had to meet was cost. After researching cameras and prices the following relationship was found: cost increases proportionally to sensitivity (not a surprising result). A camera capable of seeing in starlight could be purchased for over ten times the allowed budget and therefore was prohibitively expensive. Affordable cameras were found requiring 0.01 to 0.001 footcandle for illumination. The camera chosen for the OSU real-time system was a KOYO TVC-6200 Newvicon; it was the most sensitive camera at the least cost. The TVC-6200 requires 0.006 of a footcandle (or 0.06 lux) for a usable picture, as well as being most sensitive to light in the blue-green spectrum (38).
III. Static Experiments Involving the OSU Real-Time Neutron Radiography System

3.1 Initial Experiments

Having chosen components for the OSU Real-Time Neutron Radiography System, the time had come for testing. In the interest of consistency, some questions were proposed to evaluate each set of experiments upon their completion. These questions are:

1) What problem(s) are evident in the radiograph?

2) What is the source of the problem(s)?

3) How might the radiograph be improved and any problem(s) solved?

After posing these questions, the experimental program began by repeating the feasibility test with the new, more sensitive camera (repeating the initial experiment in Chapter Two which used the standard nine-footcandle television camera). Results were as expected: the rectangular hole in the cadmium mask was clearly visible at thirty-five kilowatts (maximum power level for steady-state operation with shutters open in Beam Port #3 under Experiment B-21, the experiment which defines procedures for high-speed radiography) and brighter than it appeared with the standard television
camera. Moreover, it was encouraging to note that an image could be seen at levels as low as five kilowatts. Figure 3.1 shows the illuminated rectangle as well as some of the imaging equipment: the concentric circles around the lighted rectangle comprise the output end of the image intensifier, and the square shape above the two circles is one of two clamps holding the mirror in place. The bright spot to the upper left of the rectangle is a reflection on the edge of the mirror from the camera's red "ON" light. Figure 3.1, along with most of the figures that follow, are photographs of images displayed on a black-and-white television screen. For more information concerning the photographic considerations see Appendix A.

Figure 3.1 is the first radiograph taken with what was to become the OSU Real-Time Neutron Radiography System. As such, this is the point where the question-and-answer process should begin. Addressing the questions mentioned previously, it is of interest to know:

a) What problem(s) are evident?

b) What is causing the problem(s)?

c) How can the radiograph be improved?

In answer to the first two questions, there are objects
Figure 3.1

Initial test of the KOYO TVC-6200
visible in the radiograph other than the desired rectangle due, apparently, to extraneous light sources (light leaks in the shielding as well as the camera's "ON" light). The image might be improved by focusing the camera so that the relevant portion of the image intensifier is more prominent in the television screen. In addition, a black plastic cover could be draped over the equipment to block the superfluous light, including the camera's "ON" light.

With the implementation of the proposed improvements, experimental work with the real-time system continued. At this point a question was raised: Could the system function without the image intensifier? Omission of the intensifier would reduce radiation damage to a very sensitive and expensive device; if the intensifier was found non-essential, it should be removed before continuing the experimental program and exposing the device to unnecessary radiation. To discover the answer an empty steel box with a scintillator attached was placed in the beam. The mirror, situated at a forty-five degree angle to the beam, allowed the camera to look directly at the scintillator. The reactor was brought to thirty-five kilowatts while the camera watched the scintillator but no light was detected by the camera. Hence, it appeared
essential to have an image intensifier to amplify the signal from the scintillator for detection by the KOYO TVC-6200. Several other scintillators previously constructed at OSU (27) were tested to discover if a better scintillator was on hand. None of these other scintillator screens performed as well as the one normally used in high-speed radiography and currently used in the real-time system.

Preliminary experiments finished, it was time to observe the system's performance with an object in the beam. Initially, it was decided to radiograph only static objects (targets that do not move) until the system had been analyzed and possible improvements employed. The chief unknown in the beginning stemmed from the fact that any object must block some of the neutrons from reaching the scintillator and forming an image: would enough neutrons strike the scintillator to produce a picture after passing through the material and losing part of their number to absorption and scattering? The object chosen for this experiment was a blank ammunition cartridge in a steel barrel because experience in high-speed radiography showed that gunpowder could be seen through the steel barrel and brass case, providing a nonhomogeneous structure with good contrast. Additionally, the bore of the barrel
could be considered as a void in a homogeneous material and should also be detectable. The barrel and the blank were radiographed in different positions and the results compared. The results were somewhat below expectations in that the image was not well resolved: areas of light and dark existed, but lacked definition. Unless one knew what the object should look like, it was difficult to discern exactly what the radiograph represented. Figure 3.2a shows a rectangular shape with a lighter triangular shape inside. The rectangle is from the cadmium mask as in Figure 3.1. The triangular shape shows the level of gunpowder in the horizontal cartridge: the gunpowder stopped the neutrons from striking the scintillator while the empty space above the gunpowder (air, see Figure 3.2b) let the neutrons pass through virtually without interaction, allowing them to strike the scintillator and produce the lighter triangular area shown.

In a similar experiment, approximately two-thirds of the rectangle was filled with the steel barrel. The remaining third of the rectangle saw only the base of a cartridge where it extended from the barrel (see Figure 3.3a). This test measured the system's ability to image high contrast light areas (air around the extended cartridge base) with dark areas (steel barrel).
Figure 3.2
Radiograph of a Small Arms Cartridge in a Steel Barrel
Figure 3.3
Radiograph of a Small Arms Cartridge Extending from a Steel Barrel
Figure 3.3b is a short-exposure print of the above described barrel with extruding cartridge. The lightest rectangle A (from Figure 3.3a) is the area without steel. The gray area B in the middle is the chamber of the barrel. The darker areas above and below area B are the top and bottom of the steel barrel. Since these areas are the thickest part of the barrel (from the viewpoint of the neutron beam) more neutrons are prevented from striking the scintillator and the resulting image is darker than other regions. Area B is lighter because it is mostly hollow due to the chamber. Area A is lightest, apparently allowing all the neutrons to pass through without differentiating between air and brass. However, by increasing the print exposure time in the darkroom, a different image appears as shown in Figure 3.3c. The longer exposure over-exposes the chamber area, but a dark shape in the position of the brass case shows faintly. Hence the system can image high contrast areas, given the ability to break down the image in parts and develop each part as necessary.

Consider Figures 3.2 and 3.3 with regard to the questions raised at the beginning of this chapter. Problems associated with these radiographs are twofold: first is a less-than-obvious representation of the ammunition cartridge and second is a significant lack of
clearly resolved features. These problems result primarily from poor resolution somewhere in the system; evidently an insufficient number of events per unit area are reaching the camera to produce a clearly defined radiograph. As to solving the problems, a slight modification of the cadmium mask could make the image easier to identify. If the mask were a forty-millimeter circle instead of its current rectangular shape (1/2 by one inch, which utilizes less than a third of the potential area), the radiograph would show more of the object and possibly facilitate identification of the image.

With the new circular mask incorporated into the system, there was still the problem of insufficient resolution in the radiograph. It would expedite matters to identify the component responsible for the poor resolution and initiate any improvements there. The specific features to analyze are the neutron beam, scintillator, image intensifier, and television camera. As determined in Chapter Two, the television unit should be operating within its range of sensitivity for both illuminance and spectral response. Nonetheless, there is a camera characteristic that could partially explain the effect observed in Figure 3.3, part A. Automatic Light Compensation (ALC) is a feature integrated into the KOYO
TVC-6200 television camera which adjusts the aperture of the lens according to the amount of light reaching the camera. The purpose of the ALC feature is to protect the television tube (sensitive to low light levels) from damage due to excessive light. A side effect of the ALC is that the lens will always adjust itself for the brightest image in its viewing area; it is thus possible for a dimmer part of the image to be unresolved if the lens closes its aperture to the point where the camera cannot distinguish between the dim image and background.

It is possible that the ALC characteristic is affecting resolution adversely; however, it is doubtful that ALC is solely responsible for the coarse images, especially given that the KOYO TVC-6200 was designed to function in these light levels. Therefore, consider the remaining components capable of inhibiting resolution: the neutron beam, the scintillator, and the image intensifier. The scintillator and image intensifier can be considered as one component since it was proven that the image intensifier was required with the specific scintillator in use. Identification of the resolution inhibitor can be determined by investigating either the scintillator/image intensifier or the neutron beam; if inquiry into one component fails to locate the poor
resolver, it can be inferred that the remaining component is responsible. Since the neutron beam is the driving force behind the entire radiography process, it seems logical to investigate the statistics of the neutron beam first, if for no other reason than to prove it is not limiting resolution.
3.2 Resolution Investigation

Problems caused by insufficient resolution evidence themselves in two primary forms: either an indefinite transition zone between contrasting areas or total obscurement of a particular region. Objects with highly contrasting neutron absorption cross sections can produce radiographs with overexposed areas (i.e., a small dark region due to neutron absorption in one spot may be hidden if the surrounding area is a weak absorber, see Figure 3.3, part A). This effect can be explained by the influence of neutron statistics on the resolution of a radiographic image.

The ability to observe detail in a radiograph is based on detecting a change of density due to a real difference rather than electronic noise. The ratio of signal to noise has been termed visibility and is described by (27):

\[
\text{visibility} = \frac{\Delta D}{\sigma(D)} \tag{Eqn 3.1}
\]

where \(\sigma(D)\) is the standard deviation of the film density caused by statistical fluctuations and \(\Delta D\) is the real density change in an object. While the term \(\sigma(D)\) refers to random variations in the density, it can be expressed as the sum of several factors which are directly applicable to real-time neutron radiography. Therefore,
let

\[ \sigma^2(D) = \sigma^2(S) + \sigma^2(I) + \sigma^2(G) + \sigma^2(N) \]  
(Eqn. 3.2)

where \( \sigma(S) \), \( \sigma(I) \), \( \sigma(G) \), and \( \sigma(N) \) are standard deviations due respectively to the scintillator screen, the image intensifier, the film graininess, and the number of neutrons contributing to the image. The last term is a function of neutron exposure, while the first three terms are dependent on the particular system used, and can only be modified by changing the individual components such as the scintillator or image intensifier. For a real-time analysis, the term \( \sigma(G) \) would be replaced by a variable describing the vertical and horizontal resolution of the television camera. However, these first three terms become less significant at low levels of neutron exposure where \( \sigma(N) \) is the predominant factor (27).

It is of interest to know whether or not images produced by the OSU Real-Time Neutron Radiography System are limited in resolution by neutron statistics. To this end, an experiment was conducted which involved radiographing a standard object. The American Society for Testing and Materials has developed devices called Image Quality Indicators (IQIs) for evaluating high energy beams (39). Radiographing these indicators gives a qualitative description of beam purity and intensity.
using a nationally recognized standard. Moreover, images of the IQIs from the OSU Real-Time System will provide a basis for comparison with other radiographic systems since these IQIs were specifically designed for evaluating neutron beams. Results of radiographing different IQIs with the OSU Real-Time System can be seen in Figures 3.4 through 3.6. Compare the radiographs to the design of actual IQIs shown in Figure 3.7.

The real-time system could detect large step changes in the IQI, but smaller step changes are not clearly separate. Figure 3.4 shows the system's ability to resolve alternating absorber and non-absorber using a Type D IQI. As the distance between absorbers decreases the resolution is lost as seen in the upper left hand corner of Figure 3.4. Figure 3.4 also demonstrates one of the problems associated with photographing a television image: the diagonal stripe crossing the lower left of the IQI is the frame separator of the television's "continuous" image. When shooting pictures at 1/30 of a second -- the same speed as one television frame -- a frame separator is bound to appear somewhere. It is often necessary to take several pictures or use the picture-freeze feature of the video-cassette recorder in order to get a photograph without a separator masking something important (see also Appendix A). Figure 3.5 shows that the system can differentiate
Figure 3.4
Radiograph of an ASTM Type D IQI
Figure 3.5
Radiograph of an ASTM Type B IQI
Figure 3.6

Radiograph of an ASTM Beam Purity Indicator
Figure 3.7
Schematic of the ASTM IQIs
between the thickest part of the Type B IQI and the next thickest, but the remaining step changes are undiscernable and the grooves perpendicular to the steps are totally lost. Figure 3.6 shows the Beam Purity Indicator as seen by a neutron beam. The holes are clearly visible as is the notch at the top of the indicator, although the image is not as sharply defined as it could be, and the changes in diameter of the holes are not shown at all.
3.3 Comparison of Neutron Exposure Between the OSU Real-Time System and Other Radiography Systems

Information gained from radiographing ASTM IQIs is helpful in describing the resolution of the OSU Real-Time System, but the results are inconclusive as to whether the limit on resolution is due to neutron statistics or the scintillator/image intensifier combination. However, recall that Figure 3.4 showed no distinction between the finer separations of the Type D ASTM IQI. Since these IQIs were designed specifically for use in a neutron beam, it seems reasonable to assume there exists a radiography system somewhere capable of resolving all areas of the Type D IQI. Why then is the OSU Real-Time System unable to resolve the total IQI?

Consider the cause-and-effect relationship between neutron statistics and television camera resolution. Neutron flux levels affect the system's resolution because the bits of information recognized by any television camera will be directly proportional to the number of neutrons per unit area. Television resolution is defined in both the horizontal and vertical directions, where horizontal resolution is dependent on the number of electrons in a given scanning line, and vertical resolution is dependent on the number of scan
lines per frame. Nonetheless, camera resolution is still largely a function of the number of neutrons available to react with the scintillator since there must be sufficient light to activate the television tube initially. Berger (3) suggests fluxes below $10^5$ neutrons/sq.cm.-second will not produce a usable image. From previous experimentation (37) the flux in Beam Port #3 is known to be $5.09 \times 10^6$ thermal neutrons/sq.cm.-second at thirty-five kilowatts. While this flux value is not less than the theoretical limit of $10^5$ neutrons/sq.cm.-second, it is close enough to investigate further, on the premise that neutron flux is the limiting factor in radiographic resolution.

One way to compare neutron exposure of the OSU Real-Time System with other radiography systems is to consider how many neutrons compose the image with respect to each individual television frame. Flux-per-frame can easily be found by dividing the flux by thirty since the KOYO TVC-6200 takes thirty frames in one second. This gives a maximum steady-state flux-per-frame value of $1.7 \times 10^5$ thermal neutrons/sq.cm.-frame. This is the maximum value because the flux measured in Beam Port #3 is incident flux, and any object will divert part of the beam, thus reducing the actual number of neutrons producing the image to something less than $1.7 \times 10^5$ neutrons/sq.cm.-frame. By comparison the incident
neutron exposure per frame in the high-speed system (assuming a 3000 megawatt pulse, 10,000 frames/second, and a 2.5 shutter allowing forty percent light transmission in the HYCAM 16mm camera) is $1.75 \times 10^7$ thermal neutrons/sq.cm.-frame, a difference of two orders of magnitude between the high-speed and real-time systems. This evidence agrees with the hypothesis that the real-time system is limited by neutron flux since the high-speed neutron radiography system works well and its resolution has been proven.

The real-time system's neutron exposure is under $2 \times 10^5$ thermal neutrons/sq.cm.-frame and close to the limit mentioned by Berger (3,8), as well as other experimenters (10,15,16,17,18,19), thus apparently allowing too few neutrons to interact with the scintillator and produce a highly resolved image. More evidence supporting the limit on resolution by neutron flux can be found in Bossi's scintillator investigation (27). Comparing the neutron exposure of Bossi's scintillator measurements to the real-time exposure, it can be seen that the real-time neutron flux is below the levels indicated by his scintillator research. Bossi reported that image quality decreased below about one kilowatt-minute for most of the scintillators he constructed, with one scintillator that worked satisfactorily down to 0.3 to 0.1 kilowatt-minutes.
Since reactor power and neutron flux are directly proportional, radiographic exposure can be measured in units of kilowatt-minutes (power x frame-time) rather than neutrons/sq.cm.-frame (i.e., flux x frame-time or number of neutrons x velocity x frame-time). Exposure in kilowatt-minutes for the real-time system is found by multiplying reactor power by the time for one frame, or thirty-five kilowatts times 1/30 of a second. Thus, one television frame receives 0.019 kilowatt-minutes of exposure, a factor of ten below Bossi's most sensitive scintillator.
3.4 Major Improvements in the OSU Real-Time Neutron Radiography System

Recall now the questions put forth at the beginning of this chapter. Problems evident in Figures 3.4 through 3.6 are still due to poor resolution, although the viewing area has been improved from Figures 3.2 and 3.3. Based on work by Bossi (27), experience with the same equipment (except for the KOYO TVC-6200) in the high-speed neutron radiography system, and the experiment involving the ASTM IQIs, it is apparent that the poor resolution is due to insufficient neutron flux. While the scintillator/image intensifier combination may be contributing to the lack of resolution, from sections 3.2 and 3.3 it is more likely that the neutron beam has the most significant impact on resolution at this stage. To improve the system's resolution, it was decided to modify the neutron beam by increasing the reactor power level by a factor of ten (thus increasing the incident flux in Beam Port #3 by ten) in lieu of researching and designing a new scintillator. If the increased flux failed to improve the radiograph, a change in the scintillator/image intensifier would be dictated by the process of elimination.

A course of action being indicated, work began which would allow radiography in Beam Port #3 at a
steady-state power level of 350 kilowatts, which is above the power level approved in Experiment B-21. This entered the realm of Feasibility Experiments (the work was performed under Experiment B-12 as opposed to Experiment B-21 since it was unknown whether increased flux would upgrade the resolution of real-time radiographs and the investigation could not be performed under Experiment B-21). The work required for the higher-power test essentially involved writing new experimental procedures which considered the increased radiation induced in the object and the potentially higher radiation exposure outside the shielding. With the higher-power experiment outlined and health physics requirements satisfied, a further modification was incorporated into the next test based on the greater viewing area due to a different cadmium mask shown by comparing Figures 3.3 and 3.4. The camera was positioned so that it actually touched the mirror (with the mirror at forty-five degrees to the beam) and focused, thus enlarging the viewing area by situating the circle of the image intensifier inside the rectangle of the television screen. A radiograph was taken of the Type D ASTM IQI with this new optical arrangement at thirty-five kilowatts, providing a basis for comparison due entirely to increased flux. This is shown in Figure 3.8: note that the finer separations are still unclear.
Figure 3.8
Radiograph of a Type D ASTM IQI at
35 Kilowatts
in the upper-right-hand corner of the IQI as in Figure 3.4, even with the increased viewing area. Now compare Figure 3.8 with Figure 3.9, a radiograph taken of the same IQI at 350 kilowatts. Observe the improved resolution in the upper-right corner and the second step change in thickness that has become evident. This experiment proves that the resolution of the real-time system can be significantly improved by an order-of-magnitude increase in neutron flux, and suggests that the scintillator/image intensifier is not a limiting factor at these flux levels.

The questions posed at the beginning of this chapter can now be considered with regard to Figure 3.9. Resolution has been improved, but it is by no means perfect. The image could conceivably be further upgraded by increasing incident flux again, but there is an upper limit since the OSTR can safely operate at a maximum steady-state power of one megawatt. Because this limit is only approximately three times the power level used to produce Figure 3.9, it would theoretically not improve resolution as drastically as an increase of ten times (the increase from thirty-five to 350 kilowatts). Moreover, since the correlation of higher flux with increased radiographic resolution has been shown, the correct method to explore real-time radiography at one megawatt would be to have a new experiment approved by
Figure 3.9
Radiograph of a Type D ASTM IQI at 350 Kilowatts
the Reactor Operations Committee to allow radiography in Beam Port #3 at greater power levels for short periods of time, or to redesign the beam port shielding for higher powers on a regular basis. Either option is plausible, but both involve potentially lengthy processes, and are beyond the overall time constraints on this project.

Nonetheless, there is another alternative which could be considered to enhance the radiograph. Recall the improved image caused by increasing the viewing area the first time (see Figures 3.3 and 3.4). Even though the change from Figures 3.4 to 3.8 was not outstanding, it might be worth asking if the image area could be further increased. Given the current configuration of image intensifier, mirror, and television camera, the area cannot be enlarged simply because of physical restraints (the camera, mirror, and image intensifier are all in contact with each other); however, this configuration is based on the assumption that the television camera should not be directly exposed to the neutron beam to avoid damage to the lens as well as the electronics inside. What if this is an unnecessary precaution? A calculation was performed to compare neutron exposure between 350 kilowatts for one minute (approximate exposure to the KOYO TVC-6200 during one radiograph at higher power) and 500 OSTR pulses
(approximate number of total exposures to the lens of the HYCAM 16mm camera used in high-speed radiography to date). Since the HYCAM lens is positioned in the direct beam, this should be an appropriate comparison. Assuming thirty-five megawatt-seconds of exposure is delivered in one OSTR pulse, the HYCAM lens has been submitted to 17,500 megawatt-seconds of neutron exposure. Likewise, one minute at 350 kilowatts will deliver twenty-one megawatt-seconds of neutron exposure. Hence, it appears that the radiation dose to the real-time system for one radiograph is several orders of magnitude below the total dose to the high-speed system. The total exposure was used because even after all the radiographs taken with the high-speed system the HYCAM lens has not become opaque to visible light; neither has the image intensifier, which is at least as complex an instrument as the television camera, and the image intensifier has always been in the direct beam during both high-speed and real-time radiography. Therefore, based on the above information, the KOYO TVC-6200 was placed directly in the beam behind the image intensifier and positioned so that the rectangle of the television monitor was situated inside the circle of the image intensifier, thus increasing the viewing area a third time.

Continuing the experimental program, a practical application was incorporated into the next test along
with the further gain in image area. It was theorized that ammunition cartridges could be non-destructively tested for the absence of gunpowder, presence of some material in place of the gunpowder, or irregularities and flaws in the bullet or case. A further motivation behind radiographing ammunition shells is that some cartridges possess a hollow area in the projectile nose (often called hollow-point cartridges). These hollow areas should be detected as voids by the real-time system much as the chamber of the barrel in Figure 3.3. Hence, a radiograph was taken at 350 kilowatts of two cartridges with hollow points, one .45 Automatic and one .38 Automatic, and is shown in Figure 3.10 (the .45 Automatic is the larger cartridge). It was encouraging to observe that the image remained visible, proving that neither the lens nor the camera electronics were incapacitated by the radiation, and confirming the prior exposure calculation. Figure 3.10 shows clearly the gunpowder, bullet, and air between propellant and projectile. The hollow area in the bullet nose is indicated in the .45 shell by the slightly lighter shading in the top and center of the bullet, but it is not obvious in the .38 cartridge. The sides of the brass casing of both shells are defined, as well as some material apparently attached to the base of the bullet, indicated by the dark area along the bottom of
Figure 3.10
Radiograph of Two Pistol Cartridges
the projectile.

It would be interesting to know how a highly resolved neutron radiograph would represent the two cartridges, and then compare that image to the real-time image. To that end a high-resolution radiograph was taken of the two shells following a procedure described in section 1.2 (see especially Figure 1.3a). The image was produced using an exposure time of three minutes at thirty-five kilowatts; a contact print is presented in Figure 3.11. Observe the clear definition of the hollow areas of both bullets compared to the real-time images, appearing rectangular in the .45 Auto cartridge and triangular in the .38 Auto shell. Even individual grains of gunpowder are visible because of the high resolution. The area at the base of the bullet is also plainly shown: from knowledge of ammunition in addition to the more refined image, it is probably the copper jacket viewed edgewise along the bottom of the bullet. Since copper has a larger neutron cross section than lead, the thin layer of copper has stopped more neutrons, creating the darker area at the projectile base.

Resolution of the film radiograph is obviously superior to the real-time image; nonetheless, the major areas (such as gunpowder and hollow point) were shown even with the coarse resolving power of the real-time system. A question may be posed as to why the film
Figure 3.11
Static Film Radiograph of Two Pistol Cartridges
radiograph is so much better resolved than the real-time radiograph when the same beam was used to produce both images. It would obviously be desirable for the real-time system to produce similarly resolved images. Consider the exposure in the film radiograph: three minutes at thirty-five kilowatts which gives 105 kilowatt-minutes. Recall that the exposure per frame to the real-time system is 0.019 kilowatt-minutes at thirty-five kilowatts (see conclusion of section 3.3). Even at 350 kilowatts the real-time exposure per frame is less than 0.2 kilowatt-minutes, or three orders of magnitude below the neutron exposure to the static film radiograph. To receive the same exposure as the film image on a per frame basis, the real-time system would have to operate with the OSTR at 189 megawatts, and this is simply prohibited by regulatory and safety requirements.

While the resolution of the static real-time radiograph (Figure 3.10) is not as impressive as that of the static film radiograph (Figure 3.11), image quality has been significantly improved from earlier radiographs such as Figure 3.2. The third increase in image area did not produce an outstanding change, but does maximize the viewing area. By far the most significant improvement to the real-time system is the factor-of-ten increase in neutron flux.
Avenues for possible improvements are limited at this stage since the reactor is already operating at near-maximum power, and if the camera is focused any closer the image may exhibit the same problem seen in Figure 3.2: a less-than-obvious representation of the object radiographed. Another television camera with increased sensitivity and resolving power could be employed; however, judging from the information presented in the experiment with FUJICOLOR HR1600 (Figures 2.5 and 2.6), light transmitted by the image intensifier is within the operating range of the KOYO TVC-6200. Moreover, the present camera has proved satisfactory thus far. This leaves the scintillator as the prime candidate for improvement. Research into scintillator performance can be a lengthy and complex process, and as such is somewhat beyond the scope of this work; in fact, theses have been written in which scintillator investigation and construction comprise a major portion of the text (26,27,40). This is not to say that the scintillator has been proven inadequate; only that if further improvements are to be made to the OSU Real-Time System, detailed scintillator research should be performed.

Consider then the OSU Real-Time Neutron Radiography System in its present stage of development: a neutron beam from the OSTR (operated at 350 kilowatts) strikes
the scintillator (composed of lithium fluoride and zinc sulfide), producing light which is amplified by the image intensifier and then transmitted by the KOYO TVC-6200 to a video-cassette recorder and monitor outside the beam port shielding. This configuration is illustrated in Figure 3.12, the difference from initial tests being the omission of the mirror (see Figure 2.7). The equipment alignment shown in Figure 3.12 will be the system used in further experiments since the components have been improved as much as possible within the constraints of this project.
Figure 3.12
Orienation of Imaging Equipment in Straight-Line Alignment
IV. Motion Studies with the OSU Real-Time Radiography System

4.1 Dynamic Non-destructive Testing

So far, all experiments have dealt with static objects and ways to improve the radiographic image. Questions posed in this chapter do not address improvements so much as they address the overall question of whether the motion of objects can be radiographed with any reasonable degree of success. In general, it is of interest to know if dynamic events can be radiographed with the OSU Real-Time Neutron Radiography System because this is one of the greatest advantages of real-time: the ability to radiograph not only static but also dynamic objects. Consequently, the next test for the real-time system was radiographing a dynamic event.

Drawing again on experience from high-speed radiography a blank cartridge could be discharged in a steel barrel following a procedure outlined by Tollefson (26). This would certainly qualify as a dynamic event; however, a superficial calculation shows the shell discharge would happen too quickly for the television unit to detect. Any modern center-fire cartridge will require on the order of one millisecond to fire; the scanning electron beam of a television camera produces a
frame (one complete picture) in 1/30 of a second. Thus, a frame lasts 0.033 of a second while a cartridge discharge lasts 0.001 of a second, meaning the camera is thirty-three times too slow to record such an event. Nonetheless, there are many other events occurring slowly enough for a television system to record.

For example, recall the idea of testing ammunition cartridges non-destructively as discussed in Chapter Three. Suppose a flaw existed on the side of the case as shown in Figure 3.10 or 3.11; it could remain undetected in that particular orientation. However, if the cartridge were caused to rotate so that it was radiographed from several angles, any flaw would certainly be discovered. To this end a platform was devised which would rotate the cartridge in a complete circle once every minute in front of the scintillator as shown in Figure 4.1. In addition, a cadmium strip was attached to the platform adjacent to the cartridge to facilitate motion detection. Using the OSU Real-Time System as described at the end of Chapter Three, a radiograph was taken of the rotating ammunition shell and cadmium strip. Figures 4.2 through 4.4 show the cartridge at different angles (when the top of the cadmium strip leans toward the right, the shell is in front of the cadmium and closest to the scintillator, a distance of a few millimeters). In this instance, there appear to be no flaws in the case or
Figure 4.1
Top View Orientation of Equipment for Rotating Cartridge Radiograph
Figure 4.2
Radiograph of Rotating Ammunition Cartridge
Figure 4.3
Radiograph of Rotating Ammunition Cartridge
Figure 4.4

Radiograph of Rotating Ammunition Cartridge
bullet. The hollow area in the bullet nose is visible as in other radiographs (Figures 3.10 and 3.11); there is also a clear distinction between air and gunpowder. Observe how drastically the cadmium strip stands out, illustrating the enormous neutron capture cross section of the cadmium atom.

The most important result from this experiment is the recording of motion without a significant decrease in resolution. As mentioned earlier, the resolving capability of the system is not perfect; nonetheless, the real-time system radiographed the cartridges in motion without a significant loss of resolution compared to the static image (Figure 3.10). Therefore, it can be said that the OSU Real-Time System has the ability to radiograph dynamic events with a moderate degree of success, realizing that the motion of one revolution per minute is at most one centimeter per second at the face of the scintillator and as such is relatively slow motion.
4.2 Real-Time Study of Two-Phase Flow

To further explore dynamic real-time radiography, consider that water in a Boiling Water Reactor (BWR) will experience two-phase flow (a single fluid moving through a channel simultaneously in two different phases, i.e., water and steam) as it rises from the lower sections of the reactor and becomes gaseous. This phenomenon is called "Departure from Nucleate Boiling" (DNB), and occurs as the water next to the fuel rod changes from liquid to gaseous phase due to the energy absorbed from the nuclear reactions. Channels between the fuel rods will consequently transport both steam and water. Air bubbles should be readily detected by a neutron beam since steam is mostly air by volume (compared to water), and because more hydrogen atoms are present in water than steam per unit volume (hydrogen having a much larger neutron cross section than air). Examination of two-phase flow in a reactor is difficult since steel is opaque to visible light. Thus, it would be beneficial and instructive to develop a system that could allow engineers to study two-phase flow under actual conditions inside an operating reactor.

Consider the mechanisms involved in causing the water in a reactor to boil. From a heat transfer perspective, a metal rod is surrounded by water and both
water and metal rod are enclosed within a steel barrier. Through a complicated series of events the metal rod transfers energy into the water in the form of heat, causing the water to boil. The question that comes to mind is how best to model this reaction so that a satisfactory radiograph is produced. Modeling a nuclear fuel rod would be a very difficult task, especially if radioactivity and temperature considerations were included. However, it is not the fuel rod so much as it is the motion of air and water in and around the rod which is the phenomenon of interest. Therefore, any method of creating air bubbles in water should prove adequate. Modeling steel and water is simple as the actual materials can be used. Following this line of reasoning, the object devised to model boiling water in a reactor consisted of a steel box open on one end (inside dimensions 5/16 by four by five inches) filled with approximately fifty milliliters of distilled water, simulating the moderator and steel case surrounding the rods in a fuel bundle assembly. Boiling was not induced directly; instead a plastic tube transferred air from a small aquarium-type air pump into the steel box, simulating DNB (see Figure 4.5).

Having devised a method to model boiling water, the system components were arranged as described at the conclusion of Chapter Three and a radiograph taken.
Figure 4.5
Photograph of DNB Model
The box was positioned so that the neutron beam was incident upon a perpendicular plane of steel and water (total thickness 9/16 inch with water contributing 5/16 inch). Still photographs of the television monitor via the video tape are shown in Figures 4.6 and 4.7. The air tube is quite obvious, and individual bubbles can be seen with the video-cassette recorder in single-frame-advance mode. It is interesting to note that a single bubble takes about three frames to travel from the bottom to the top of the screen, an actual distance of approximately forty millimeters, the diameter of the input end of the image intensifier. Since one television frame lasts 1/30 of a second, the bubble has a speed of approximately forty centimeters per second. Compared to the rotating shell of Figures 4.2 through 4.4 (about one centimeter per second), this is a much faster event. Resolution is still coarse, but it did not decrease significantly from previous radiographs (Figures 3.10 and 4.2). The individual bubbles are not clearly defined, but that could be due to their motion in addition to the imperfect resolution since there is an inherent difficulty in producing a still picture from a dynamic event (i.e., blurring), especially when constrained by the television system to shutter speeds of 1/30 of a second of more. Moreover, it is worth noting that the images from the video monitor
Figure 4.6
Radiograph of DNB Model
Figure 4.7
Radiograph of DNB Model
were easier to interpret than the still photographs taken of the video images (especially Figures 4.6 and 4.7). It can thus be argued that the OSU Real-Time Neutron Radiography System, while not producing outstanding results, adequately performed the task of recording certain dynamic events since motion was observed and the radiographs could be interpreted without overwhelming difficulty.
V. The OSU Real-Time Neutron Radiography System in Retrospect

5.1 Conclusions and Recommendations

The real-time neutron radiography system developed at OSU broke new ground in radiography techniques at Oregon State. Successful events include the conception, procurement, and completion of a working real-time system, as well as radiographing two dynamic processes (rotating cartridge and air bubbles in water). The major setback is the lack of clearly resolved images. Nevertheless, feasibility of a real-time system was hypothesized and proven, and the system was assembled.

The one factor of the OSU Real-Time Neutron Radiography System most in need of improvement is resolution. To that end consider the components of the real-time system and what can be done to improve them: neutron beam, scintillator/image intensifier, and television camera. Collimators used in Beam Port #3 for the neutron beam are already in the optimum range as mentioned in section 2.1; hence, the best way to improve the beam is to increase its number of particles per unit time. This can be done easily by operating at a higher power level, as shown in section 3.4 by radiographing ammunition cartridges at 350 kilowatts, since flux and
power are directly proportional. To further increase flux the reactor would have to operate at its maximum power of one megawatt. As this is only (approximately) three times greater than 350 kilowatts, it is questionable whether one megawatt would show as drastic an improvement in resolution as the factor of ten increase from thirty-five to 350 kilowatts. Nevertheless, it could hardly be detrimental. Two problems come to mind when considering radiography at one megawatt: first, the shielding surrounding Beam Port #3 is sufficient for thirty-five kilowatts, but additional shielding would be required if the reactor operated at a higher power on a regular basis. Second, the object radiographed would become more radioactive because more neutrons would interact with the target. While this poses a handling problem, health physics practices already followed at OSU would prevent any major contamination problem.

Improvements initiated in the remaining components would essentially require replacing the current equipment with devices having enhanced characteristics. Since the scintillator chosen for real-time work was actually designed for high-speed radiography, it is quite possible the scintillator or image intensifier could be changed to enhance resolution: some evidence suggests a gadolinium-type scintillator would optimize
the neutron signal for real-time applications (12,40). Further research and experimentation could probably develop a more efficient scintillator specifically designed for real-time radiography. As for the image intensifier, a unit with higher gain has been commercially manufactured, but the cost is substantial. Besides, it makes little sense to invest in a new image intensifier without investigating scintillators thoroughly.

As a final consideration, the last component capable of improving resolution is the television camera. While the cost is again substantial, cameras with greater sensitivity and/or resolution are available. However, if there exists a physical limitation such as insufficient neutron flux, then increased camera sensitivity would not improve the resolution given the current flux levels, scintillator, and image intensifier. Therefore, considering all the solutions presented so far, the alternatives with the most promise for better resolution of any object or event are: 1) investigation into a scintillator specifically designed for real-time radiography, and 2) modifying existing procedures and equipment to regularly radiograph at one megawatt.
5.2 Applications

Even though the OSU Real-Time Neutron Radiography System has not performed up to all expectations, application of the real-time technique could be very helpful in a number of areas. Non-destructive testing could be accomplished if manufactured goods were caused to pass through a neutron beam (probably from a reactor), thereby inspecting products so that defects could be identified immediately. It is worth noting that if the defects were large enough to accept gross resolution (i.e., highly resolved images were not required), the OSU Real-Time System could perform non-destructive testing so long as the size of the defect was within the resolving capability of the system.

Used in conjunction with the high-speed system, the real-time system could facilitate alignment of objects and equipment for high-speed motion radiography since the current methods rely partly on examination of the high-speed films after irradiation. Another application at OSU can be theorized by closer examination of Figures 4.3 through 4.6. Observe a small dark spot slightly above and to the right of direct center in each of the television images. The spot does not appear to change position in any of these radiographs, which indicates
the spot is on the scintillator itself. Newly constructed scintillators could be tested for consistency by using the real-time system to look for similar dark spots or inhomogeneities as shown in Figures 4.3 through 4.6.

Real-time neutron radiography could greatly facilitate investigation of various flow phenomena such as two-phase flow, flow disruption in a channel, verification of heat transfer correlations, and models for boiling. Recall the ideas in section 4.2 concerning two-phase flow in a BWR. In a similar application, a Pressurized Water Reactor (PWR) can experience boiling under certain accident conditions; the real-time technique could be used for modeling accident situations or monitoring fluid flow in a correctly functioning PWR so as to be aware of possible problems. Potential research in flow disruption as outlined by Tollefson (26) would also benefit from the real-time system, especially from the larger viewing area (i.e., forty-millimeter-diameter circle instead of one by 1/2 inch rectangle).

A beneficial modification to the real-time system could be the adaptation of color imaging and/or digital enhancement. This would require some sort of computer manipulation as discussed by authors mentioned at the end of section 1.3 (22,23,24,25). Color images could
make the radiograph easier to interpret by relating
density differences in the neutron beam to colors in the
visible spectrum, and computer enhancement could bring
out details normally overlooked. Another method of
highlighting density differences is the judicious choice
of materials in the object radiographed. For example, if
heavy water is used to simulate boiling water in a
reactor, individual bubbles might be successfully imaged
because of deuterium's low cross section for scattering
compared to hydrogen. As another example, recall the
rotating shell of Figure 4.2. If a grease or oil based
on gadolinium (or some other high-neutron-cross-section
material) were smeared over the case and bullet, minute
cracks and/or surface voids would become obvious. Many
such applications are possible, the single most
important restriction being how the object or event will
interact with the neutron beam.
VI. BIBIOGRAPHY


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Appendix
APPENDIX A

Suggestions for Photographing Television Screens

The most important fact in photographing television images is the speed at which the images are displayed: thirty frames per second. Hence, to get one complete picture the shutter must be open 1/30 of a second. Pictures taken with exposures greater than 1/30 of a second will integrate the image on the film, giving two pictures (one on top of the other) for a one-fifteenth second exposure, about four pictures for a one-eighth second exposure, and so on. This is not an entirely undesirable effect since details can sometimes be enhanced by the integration. It can be helpful to keep the television image constant (put the video cassette recorder on "PAUSE") in order to repeat the exact frame several times; however, the pause mode can also introduce noise into the picture. On a further note, the bar separating individual frames cannot be avoided using either focal plane or aperture shutters, but integrating frames on the film can decrease their significance. Moreover, electronic timers exist which can coordinate television frames and shutter timing so that no frame separator appears.
The speed requirement means the camera cannot be hand-held or the picture will blur. Two accessories are thus necessary: a tripod and a way to remotely activate the shutter (a cable release works well). The camera should be positioned directly in front of the television screen in a room where all the lights can be turned off so that only light from the television will expose the film. Type of film is, of course, an important consideration. A fast film is needed since there is really very little light (Kodak Tri-X pan, ISO 400 works well). To get maximum resolution from screen to film a small F-stop should be used, such as F-16 or F-11. One final suggestion involves the video-cassette recorder and thus is applicable to each machine and its capabilities: slow-frame-advance and stop-frame modes are excellent for photographing specific frames. For best results using the Quasar VH5041XW, record with Super Long Play (SLP) rather than Long Play (LP) or Standard Play (SP) so that playback images will be relatively free of static.