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MASTER

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SUMMARY

A hand-held instrument for monitoring irradiated nuclear fuel inventories located in water-filled storage ponds has been developed. This instrument provides sufficient precise qualitative and quantitative information to be useful as a confirmatory technique to International Atomic Energy Agency inspectors, and is believed to be of potential use to nuclear fuel managers and to operators of spent-fuel storage facilities, both at reactor and away-from-reactor, and to operators of nuclear fuel reprocessing plants.

Because the Cerenkov radiation glow can barely be seen by the unaided eye under darkened conditions, a night vision device is incorporated to aid the operator in locating the fuel assembly to be measured. Beam splitting optics placed in front of the image intensifier and a preset aperture select a predetermined portion of the observed scene for measurement of the light intensity using a photomultiplier (PM) tube and digital readout. The PM tube gain is adjusted by use of an internal optical reference source, providing long term repeatability and instrument-to-instrument consistency. Interchangeable lenses accommodate various viewing and measuring conditions.

INTRODUCTION

An instrument has been designed, built, and tested for monitoring irradiated nuclear fuel assemblies located in a water-filled storage pond. This instrument measures the intensity of the Cerenkov radiation emitted from the fission products in the nuclear fuel. This intensity is then compared with the intensity expected for a nuclear fuel assembly having a corresponding degree of exposure and cooling time after removal from a reactor core. For an assembly having coolant channels, the Cerenkov light intensity measurement is taken over an area of the assembly containing a number of bright spots corresponding to the assembly coolant channels. These coolant channels act as Cerenkov light channels and serve to reduce the cross-talk among adjacent assemblies.

The instrument is composed of two basic components. The image amplifying portion is commonly known as a night vision device and will be referred to herein as a Cerenkov Viewing Device (CVD). An electro-optical package that reflects part of the incoming Cerenkov light, with a beam splitter, through an aperture and a field lens is added to this CVD. The Cerenkov light is then reflected by a mirror onto a PM tube that responds in a well-known manner to the intensity of the light. The PM tube output-current measuring circuit provides a digital readout indication of the intensity of the incoming light.

A detailed description of the instrument, its potential applications, appropriate background and theory, and a summary of previous measurements made of the Cerenkov light emitted by irradiated fuel are given in this report.

BACKGROUND

A large fraction of the special nuclear material (SNM) inventory in the nuclear fuel cycle, both domestic and international, is contained in irradiated fuel assemblies in the form of plutonium and unburned ^{235}U. Because of the implications of nuclear proliferation in the international arena, and the potential for diversion domestically, the safeguarding of this material has become a subject of great interest. Techniques and instrumentation that allow for the confirmation of declared irradiated fuel inventories in storage ponds at both reactor and away-from-reactor (AFR) installations have resulted in a number of studies that address this problem. Under the U.S. program for technical assistance to international safeguards, the Detection and Verification group (Q-2) at the Los Alamos National Laboratory has evaluated[1] eight possible attribute measurement techniques that would provide confirmation of irradiated fuel. The criteria used for selecting promising techniques included ease of implementing the technique, simple interpretation of the measurement data, and minimal impact on the facility operators' routine schedule. Adherence to these criteria precludes any movement of fuel assemblies. In addition, simple interpretation of the measurement data eliminates the sampling of nuclear radiation fields above the assemblies because interpretation of this data would require complex unfolding algorithms.

Of the eight techniques evaluated, the most promising technique that satisfies the criteria is the Cerenkov glow intensity measurement technique. It is the only technique investigated that does not require disturbance of the storage ponds yet provides quantitative, as well as qualitative, information for confirmation of the attributes of irradiated fuel. Because water has a very small attenuation coefficient for visible and near-ultraviolet light, the measurements can be made from the storage pond surface, thereby allowing them to be made with all instrumentation totally out of the water. For the standard vertical assembly storage, the penetrations in the upper mechanical structure of the assembly, as, for example, in a pressurized water reactor (PWR) assembly, and the interstices between fuel pins, as in boiling water reactor (BWR) assemblies, serve as Cerenkov light channels and allow the sampling of the nuclear radiation intensity to be much deeper than the top of the fuel assembly. This measurement is also much less susceptible to cross talk among adjacent assemblies than are nuclear radiation intensity measurements made at the tops of the assemblies.

THEORY

Cerenkov radiation is produced whenever a charged particle passes through a medium at a velocity greater than the phase velocity of light in that medium. In water, for example, any electrons with energies greater than 0.26 MeV kinetic energy will produce Cerenkov radiation. In the case of spent fuel, the origins of these energetic electrons include Compton electrons produced by gamma radiation, beta rays that escape directly into the water, and the interactions of high-energy neutron capture gamma rays that produce electrons from Compton scattering and pair production. All of these sources of high-energy electrons are produced from the decay of fission products. It was expected, and later experimentally shown to be true,[2] that the intensity of Cerenkov light generated by the irradiated fuel is proportional to the radiation field intensity in the vicinity of the irradiated fuel. This field intensity is proportional to the burnup of the fuel and inversely proportional to the cooling time.

The number of Cerenkov photons generated by gamma rays of any energy passing through water has been calculated in earlier reports.[1,2] The results of these calculations have been verified experimentally. The theoretical basis for the Cerenkov technique has been described in some detail in the earlier referenced reports and will not be repeated here. We have calculated the Cerenkov light intensity as a function of exposure and cooling time. These calculations were used as the basis of comparison of the experimental data obtained at various facilities.

INSTRUMENT DESIGN

The spent fuel monitor instrument consists of two major assemblies: The Cerenkov Viewing Device (CVD), and The Cerenkov Measuring Device (CMD). The CMD is attached to the CVD between the lens and image intensifier and contains beam splitting optics to allow both viewing and measuring the target.

CERENKOV VIEWING DEVICE

This device is a Varo Noctron V night vision device with a 3 in. biocular viewer, for viewing the scene with both eyes, and an assortment of Olympus "T" mount 35-mm lenses. The Noctron V uses a Gen II 25-mm image intensifier with automatic brightness control. It is self-contained, with batteries in the handle, and has a "low-battery" test feature.

The biocular viewer can be easily removed and replaced with an monocular eyepiece or an adapter for a 35 mm camera. A special film graticule has been made and placed between the biocular viewer and the image intensifier showing the target areas corresponding to the different aperture sizes. This allows the operator to see the area of measurements.

Figure 1 shows the Noctron V before attaching the CMD electronics and optics.

CERENKOV MEASURING DEVICE

This electronics and optics package is made to attach to the Noctron V to form the completed instrument. All the beam splitting optics are contained and pre-aligned in this device such that no special modifications are required to the Noctron optics. The only modification is the addition a switch to the handle of the Noctron to allow the operator to "freeze" the reading on the display. Figure 2 shows the assembled instrument.

A block diagram of the spent fuel monitor is shown in Figure 3. The beam splitting cube divides the incoming light between the image intensifier and the measuring device. Various apertures are provided to allow the operator to choose the area of the scene he wants to measure.

The heart of the measuring device is the photomultiplier (PMT) circuit, amplifier, and A/D converter display. The PMT is a 12-stage device operated from a 1200-V dc-dc converter. The 1200-V supply is adjustable by the operator and controls the gain of the PMT. The PMT output is dc coupled to a low-noise operational amplifier with a 0.5-s integration time. The op - amp output is scaled to between 0 - 2 V, and is digitized and displayed by a Texmate PM-45X digital panel meter with a liquid crystal display (LCD). The LCD was chosen for its low power consumption, but has a drawback in that it requires illumination to be read in the dark. This was resolved by using an electro-luminescent pane installed directly behind the LCD and powered by a dc-ac converter.

The dynamic range of the PMT/amplifier is about 3 neutral-density (ND) filter ranges, with a resulting output of 0-1.5 V. A circuit is used to detect a level of 1.6 V and light a lamp to indicate an "overrange", or too bright an input scene. Provision is made to allow insertion of a ND filter in the PMT optical path to reduce the light level. A switch on the instrument is then set to the ND number, which changes the decimal setting on the display. This allows the instrument to yield the same number on the display for a given light level, regardless of ND filter used.

Calibration of the instrument is done by using a carbon-14/phosphor light source built into a special lens cap. A dark slide is inserted in the optical path and the "dark current" of the PMT is adjusted to read zero on the display. The dark slide is removed and the light source installed on the lens. The PMT gain is adjusted to a predetermined number on the display. This number corresponds to a calibration factor determined for the light source, providing for instrument-to-instrument repeatability. Calibrating the instrument with an external light source was chosen to allow the entire system, including lens, to be included in the calibration.

A shoulder pack 12-V battery was selected to power the instrument. This battery powers the unit for many hours. It also can be recharged from an automobile cigarette lighter, providing field recharge capability.

The mechanical package was designed to be rugged, small, and easy to adapt to the Noctron CVD with a minimum of modification. The instrument is the first version, and is considered a "fieldable breadboard" for use by the Los Alamos National Laboratory, EG&G, and the IAEA to evaluate its effectiveness and features.

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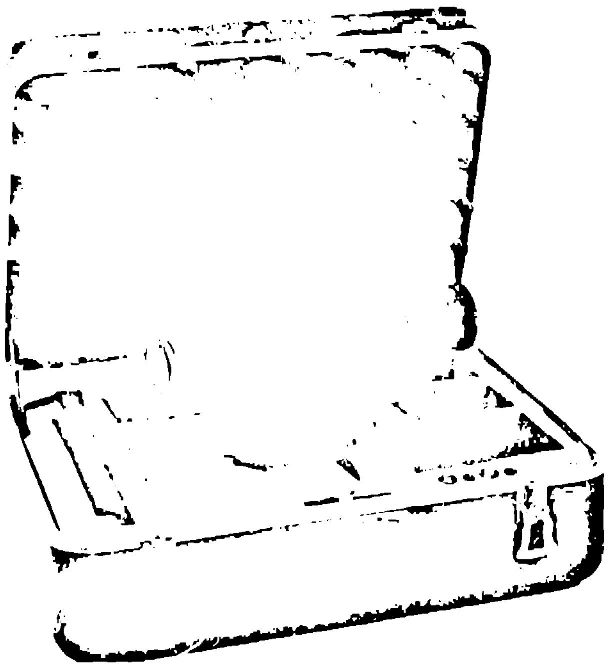

FIGURE 1.

FIGURE 2.

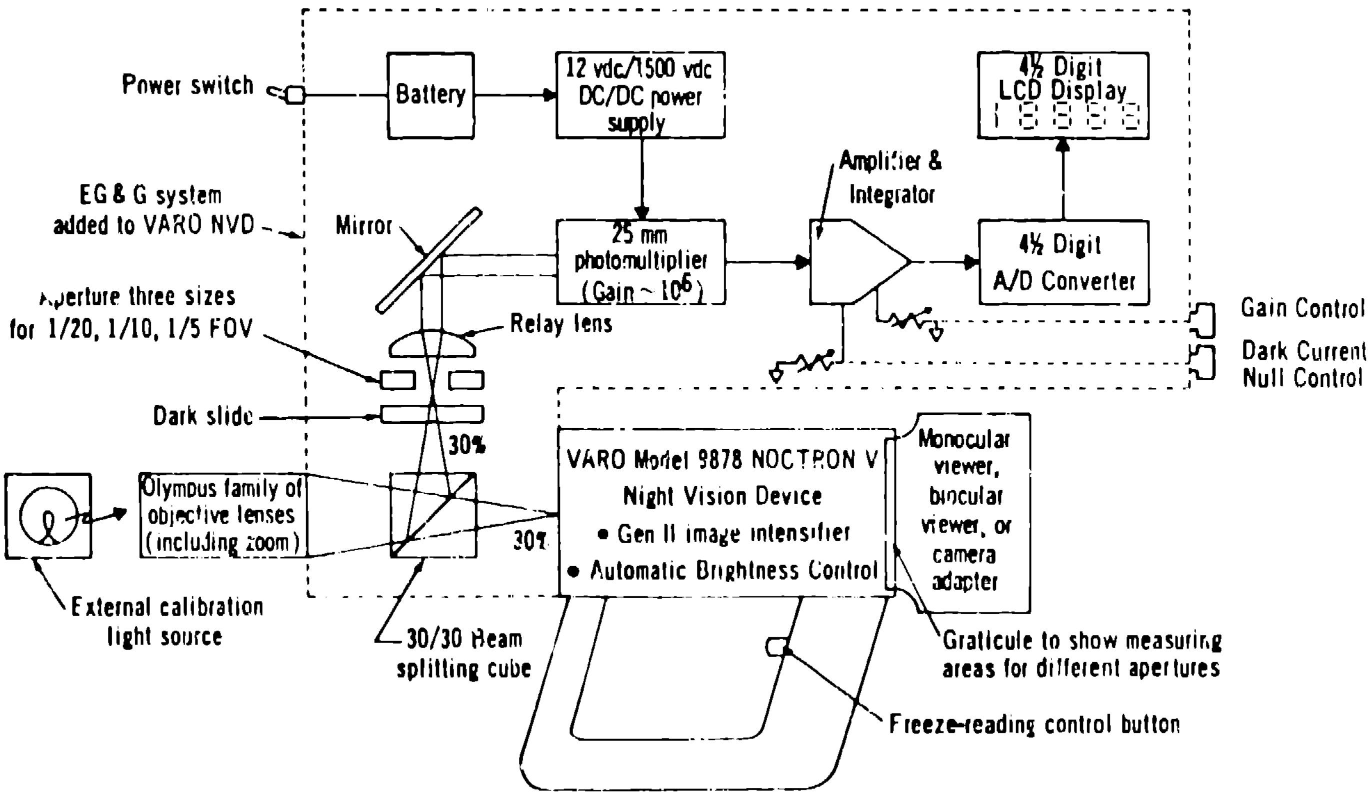

FIGURE 3.

SUMMARY OF EXPERIMENTAL PROCEDURES AND EQUIPMENT

The Cerenkov light generated by materials testing reactor (MTR), PWR, and BWR fuel is highly collimated when viewed along the axis of the assembly. This is the normal view for light water reactor irradiated fuel because this fuel is stored vertically and viewed from above the pond from a bridge that spans the storage pond. The highly collimated nature of the light requires that the instrument used to measure the Cerenkov glow have its optical axis positioned along the axis of the assembly to view the maximum light intensity emitted by the assembly.

Experimental data have been obtained at the Los Alamos National Lab's Omega West Reactor (OWR) (an MTR), at the Zion nuclear station (with two PWRs), at the Morris irradiated fuel storage facility, (which contains both BWR and PWR fuels), and at the irradiated CANDU fuel storage bay at the NRX facility at the Chalk River National Laboratory. The measurement techniques at these installations varied and included the use of a silicon intensified target (SIT) video camera at the Los Alamos MTR reactor and the Zion nuclear station; a Pritchard photometer coupled by a transfer lens to an RCA ISIT video camera; a Javelin model 226 CVD coupled to a 35-mm camera to record the image on film at the General Electric Morris facility; and the Javelin model 226 CVD was also used at the Chalk River facility. The data obtained using video equipment were analyzed using a video editor. A single frame of video information could be frozen, allowing an associated electrometer to measure the intensity of a single pixel element out of a 512 x 512 matrix of pixels that forms the video image.

These data all confirm that the intensity of Cerenkov light generated by irradiated fuel assemblies is proportional to the burnup and inversely proportional to the cooling time of the assembly.

APPLICATION OF THE CERENKOV TECHNIQUE TO AFR'S

It is anticipated that the IAEA inspectors will be using the Cerenkov glow imaging and measuring technique for verifying the inventories of irradiated fuel at reactor and AFR facilities throughout the world. Furthermore, the technique will most likely be adopted in a gradual fashion as more inspectors become familiar with its use and the simplicity and speed that the technique and the instrument offer. At present, the inspectors routinely read only the serial numbers from the assemblies. Additional non destructive assay (NDA) measurements can be made, but these are difficult and time consuming. The Cerenkov technique provides the inspectors with an attribute measurement capability that is rapid, easy to perform, and somewhat difficult to spoof.

The Cerenkov glow technique will also be useful to the facility operator by providing him with a rapid means of verifying incoming and outgoing shipments of irradiated fuel and in inventory control of the irradiated fuel in a storage pond. Another feature of this technique that the facility operator will find useful is the ability to obtain a rapid intensity profile measurement of the irradiated fuel in his inventory. The profile of the radiation intensity of an irradiated fuel assembly will provide a good estimate of the uniformity of the burnup which will result in a better estimate of the fissile content of each assembly in storage.

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