REACTOR POWER MONITOR BASED ON CHERENKOV RADIATION DETECTION*

K. G. Porges, R. Gold and W. C. Corwin
Argonne National Laboratory
Argonne, Illinois 60439

Summary

At the temperature and radiation levels expected in the core region of some projected reactor plants, conventional radiation sensors, such as fission chambers, suffer severe radiation damage. On the other hand, remote location of sensors introduces geometry effects. These circumstances emphasize the need for a power level sensor which is highly resistant to the hostile environment and still responds directly to power level changes.

Such a detection channel has been proposed. It is based on sensing the gamma flux above some energy threshold, thus discriminating against gamma radiation associated with decay. In addition, the proposed system dispenses with cables and voltages applied across damageable insulators, through sensing the light transmitted along a cylindrical duct. The detecting medium is the gas with which the duct is filled; the light signal is the Cherenkov radiation generated by relativistic Compton recoil electrons.

Cherenkov radiation intensity increases sharply from an electron velocity threshold, which depends on the index of refraction of the medium. For gases, this threshold can be continuously varied by adjusting the gas pressure. On the other hand, electrons with subthreshold velocities can generate (background) light through scintillation processes.

In order to assay the overall discrimination available from the choice of gas, pressure, and geometry, a series of tests has been under way with 3-MeV electron pulses from a Van de Graaff accelerator. The detector used in these tests was filled with various gases at pressures ranging from 0 to 1000 psi, and the intensity of photomultiplier pulses was recorded as a function of pressure, by means of an address-averaging system fed by an ADC; photomultiplier pulses were gated by the accelerator.

Measurements made thus far with a few gases show excellent agreement with theoretically calculated Cherenkov yields and demonstrate a rise of more than two orders of magnitude in intensity from threshold.

Introduction

Future liquid metal-cooled, fast breeder reactor (LMFBR) plants of 1000-MWe (2400 MWt) power generating capacity, currently under study, will develop a gamma intensity of 10^{21} photons/sec and a fast neutron flux up to 10^{14} n/cm^2 sec, with coolant temperatures in the vicinity of 1000°F. When such a plant is controlled by means of conventional sensors, i.e. fission chambers, it is necessary to locate the latter at some distance from the core in order to prevent rapid deterioration through radiation damage in the necessary insulation and depletion of the fissionable coating. However, as detectors are removed from the vicinity of the core and thus placed in a milder environment, geometric effects become appreciable. This quandary leads to the search for power-sensing devices which can tolerate very high temperature and radiation levels; in particular, such a device should have no depletable coating and preferably should not require voltages across insulators exposed to high fast neutron flux levels.

Any useful sensor must indicate the power level with adequate sensitivity and speed of response. Sensors which respond to neutrons satisfy this requirement, since the neutron flux is strongly correlated with the fission rate, hence reactor power. As regards the gamma radiation produced by the reactor, only that fraction of the gamma flux which originates in <u>prompt</u> processes (capture and fission) varies with the power level; copious gamma radiation is also emitted by <u>decay</u> processes originating from induced activities and fission products. Since conventional gamma detectors cannot discriminate to a practically useful extent against this delayed gamma component, neutron detectors have become standard; moreover, considerable efforts have been made to reduce the gamma sensitivity of these sensing channels.

It may be pointed out, however, that the gamma spectrum associated with decay rapidly falls off above 1 MeV, whereas the spectrum associated with prompt events has a relatively strong component at considerably higher energies. If, therefore, an energy discrimination principle which has a response threshold somewhere between, say, 2 and 5 MeV can be incorporated into a gamma detector, the resulting instrument should meet the requirement of rapid response to power level.

A detection channel which has such a threshold feature and also appears to satisfy radiation and heat resistance specifications to a much larger degree than other known systems has been recently proposed. It is based on the detection of the <u>Cherenkov</u> light generated by Compton recoil electrons which originate in scattering processes involving only the high-energy component of the gamma flux. The Cherenkov effect is characterized by a sharp threshold, depending on the index of refraction of the medium. For gases, the index of refraction is a unique function of the density and can therefore be adjusted over a considerable range. This allows one to choose the Cherenkov

Work performed under the auspices of the U.S. Atomic Energy Commission.

threshold anywhere above about 2 MeV at technically feasible pressures, for a variety of gases and gas mixtures.

The detector simply consists of a long metal tube or channel, one end of which is located in or near the reactor core. The opposite end is equipped with an optical system designed for the transmission of light out of the primary reactor enclosure to an optical window viewed by a photomultiplier tube. The metal channel is filled with a given gas to a suitable pressure. The gas-filled channel thus serves both as the detecting medium and as the signal transmission line.

The use of Cherenkov light for power level sensing has been proposed previously.[1-4] It may be pointed out, however, that these proposals considered solid (or liquid) Cherenkov media which would remain unaltered only in a relatively mild fast neutron flux. Moreover, such media do not provide threshold discrimination. On the other hand, the effectiveness of energy discrimination for any Cherenkov medium is adversely affected by its possible susceptibility to scintillation--which, for the case of a gas, includes recombination radiation. The intensity, time dependence, and spectrum of this light emission varies in a very complex manner with gas pressure and impurity level. The best choice of pressure, type of gas, possible admixtures, and color filters is thus most readily determined on the basis of tests with monoenergetic electrons. Preliminary results of a series of such tests are reported below.

Experimental Arrangements of Van de Graaff Tests

One-nanosecond long pulses of 3-MeV electrons were obtained from a Van de Graaff acelerator. The beam was passed through a detector head equipped with thin entrance and exit windows, shown in Fig. 1. A 45-deg mirror, made from 0.001-in. aluminum foil stretched over a frame, deflected any light originating in the front part of the detector head down a lateral light guide and towards another 45-deg mirror. After another short straight section, the light guide was closed with a quartz window, viewed by a photomultiplier (RCA 8575). A set of movable filters or neutral light attenuators could be inserted between the quartz window and the photomultiplier face. The detector, attached to a conventional gas filling and evacuation system, was designed to withstand up to 2 kpsi gas pressure.

To measure the light intensity as a function of gas pressure (hence index of refraction), it was necessary to average over a suitable number of beam pulses, since (a) the input intensity fluctuates somewhat from pulse to pulse about a stabilized average; and (b) statistical processes in the collection of light in the photomultiplier broaden the pulse-height distribution--a contribution which dominates at weak light intensities. Background, dark current and pickup noise were excluded by fast gating. Data were taken by passing photomultiplier anode pulses through a gate opened by a pickup signal from the accelerator, stretching these pulses to a few microseconds and digitizing the resultant pulse height in an ADC system; ADC address advance pulses were accumulated in a scaler and also fed to a multichannel analyzer for inspection purposes. Another scaler was used to count off exactly 100 beam pulses, a process which could be repeated a few times when necessary until statistics were adequate. This allowed relatively rapid data acquisition in the regions where intensity does not change rapidly with pressure. Where the Cherenkov light becomes intense, a number of stratagems were tried to circumvent saturation problems arising in the photomultiplier: a parallel output channel was taken off the first dynode, or from some other dynode, gain or attenuation was inserted between PM output and gate input and light attenuators were inserted between detector window and photomultiplier. It was thus possible to intercalibrate over three orders of magnitude of actual intensity. To guard against saturation, shapes of PM pulses were also observed by means of a sampling scope. Fast signals were run through shielding walls by means of special pulse transmission lines.[5] Gas pressure was measured on a precision Bourdon gauge.

Results

The dependence of light intensity on gas pressure is plotted in Figs. 2 and 3, for methane and ethane, respectively. The figures also show the relative theoretical Cherenkov yield, calculated as discussed below. The measurements evidently follow theoretical prediction reasonably well except for the region well beyond the threshold, where the observed light intensity drops off. This may be ascribed to light loss upon reflection from the walls of the apparatus, which one would expect to increase with increasing Cherenkov angle, from the relation

$$\cos\phi = (n\beta)^{-1} ,$$

where $\beta = v/c$, v = electron velocity, while n = index of refraction. The threshold gas density N_t is related to the threshold index of refraction $n_t = 1/\beta$ and the NTP index of refraction n_0 through the Lorentz-Lorenz law. This can be conveniently expressed in the form

$$\frac{1 + k/6}{2k(\gamma^2 - 2/3)} = N_t/N_0 ,$$

where N_0 = Loschmidt's number and γ has its usual meaning $(1 - \beta^2)^{-\frac{1}{2}}$. The parameter $k = n_0 - 1$ ranges between about 2×10^{-4} and 6×10^{-4} for most suitable gases, with the important exceptions of helium ($k = 0.4 \times 10^{-4}$) and hydrogen ($k = 1.2 \times 10^{-4}$). The pressure dependence of the gas density must be calculated from an equation of state which is valid at the relatively high pressures of these tests, such as Van der Waal's.

The dependence of the observed intensity below this threshold on the gas pressure is somewhat influenced by the experimental geometry due to the prevalence of scattering. The second mirror, shown in Fig. 1, was absent in some of the runs, allowing a certain amount of scattered gamma flux to impinge on the quartz window where it excited scintillations (scattered electrons were successfully removed by means of a magnet). The remaining light intensity must be ascribed to various types of radiative processes, some of which involve binary collisions and thus would be expected to vary with the second power of the pressure. Amongst such processes, one cannot rule out the possibility of Cherenkov light generation in the far UV, followed by rapid absorption and reradiation through which isotropic light in the visible spectrum, indistinguishable from "scintillation" light, is emitted. The isotropic component of the light emitted above Cherenkov threshold was investigated in some runs by turning the mirror through 90 deg, so as to reflect light generated in the part of the detection chamber located behind the mirror pivot. Any direct Cherenkov light generated in that part of the chamber should be largely absorbed on the blackened surfaces facing the electron beam, hence only that component of isotropic "scintillation" light which was emitted backwards, towards the mirror, is observed. Some data obtained by repeatedly turning the mirror are shown in Fig. 4, for methane. These measurements indicate that the epi-Cherenkov threshold isotropic component is about that which one might infer by a rough extrapolation of the subthreshold yield.

The light yield for nitrogen, shown in Fig. 5, shows no recognizable structure. Apparently the intensity of "scintillation" processes completely masks the Cherenkov yield in that gas, which is thus unsuitable for energy discrimination. Similarly, threshold discrimination was found to be poor in argon and in helium, whether a commercial grade or a highly purified gas was used. The subthreshold light yield for helium was found to be fairly strongly quenched by admixtures of methane, as shown in Fig. 6.

Discussion

For some of the limited number of gases tested thus far, the data tend to confirm the technical possibilities of energy discrimination, while other gases, especially nitrogen, are shown to be unsuitable. One of the interesting results of these tests is the usefulness of a relatively simple model in predicting the Cherenkov yield. The predictions shown as a smooth curve in Figs. 2 to 4 were calculated by integration of the Tamm-Frank formula[6] from the incident electron energy down to the threshold. The electron energy loss per unit path length was approximated as constant over the energy region of interest (in this region, dE/dx is at its minimum value and varies only slightly over a broad energy range). The absolute yield would further require the exact quantum efficiency of the photomultiplier used, as well as the exact light transmission efficiency of the apparatus; without that information, the yield is only relative and the curves shown in Figs. 2 to 4 are thus adjusted on the ordinate to give the best fit. At higher pressures, incident electrons will strike the mirror before reaching their threshold energy; this effect was corrected for. The predicted yield comes to

$$Y \sim \left(\gamma_i - \gamma_t\right) \frac{n^2 - 1}{n^2} + \frac{1}{2n^2} \ln \frac{\left(\gamma_i + 1\right)\left(\gamma_t - 1\right)}{\left(\gamma_i - 1\right)\left(\gamma_t + 1\right)} ,$$

where the subscripts i and t denote initial and threshold values, respectively.

Tests of other gases and gas mixtures are now under way, in which color filters are also inserted to enhance or depress the relative contributions of scintillation and Cherenkov light.

References

1. J. V. Jelley, *Prog. Nucl. Phys.*, 3, 84 (1953); also *Cherenkov Radiation and Its Applications* (Pergamon Press, New York, 1958).

2. K. Skarsvag and A. Lundby, "Cerenkov Radiation from the Heavy Water in JEEP," JENER Report No. 22 (Kjeller, Norway, 1953).

3. J. L. Lovvorn, "Reactor Power Monitor Utilizing Cherenkov Radiation," *IRE Trans. Nucl. Sci.*, 8, No. 4, 3 (1961); also S. E. Rippon, "Cherenkov Detectors for the Measurement of Reactor Power," *Nucl. Instr. Method*, 21, 192 (1963).

4. H. Weiss, "Power Measurement and Automatic Reactor Control by Cherenkov or Gamma Radiation," *Proceedings of Conference on Nuclear Electronics, Bombay, 1965* (IAEA, Vienna, 1966), p. 461.

5. K. Porges, W. Corwin, L. Burkel and E. Lewandowski, "Signal Transmission Line With Low Attenuation and Wide Frequency Passband," *Rev. Sci. Instr.* (to be published).

6. I. Frank and I. Tamm, *CR Acad. Sci. USSR*, 14, 109 (1937); also P. A. Cherenkov, *Phys. Rev.*, 52, 378 (1937).

NOTE ADDED IN PRINT: It has been recently brought to our attention that a test of a gas Cherenkov reactor power monitor was previously reported by W. K. Lehto and J. M. Carpenter, *Nucl. Appl.*, 3, 750 (1967). The principle of such a detector was further described in a note by W. K. Lehto and J. M. Carpenter, *Trans. Am. Nucl. Soc.*, 9, 478 (1966), and in Mr. Lehto's Ph.D. thesis, Univ. Michigan, IP-793 (1967).

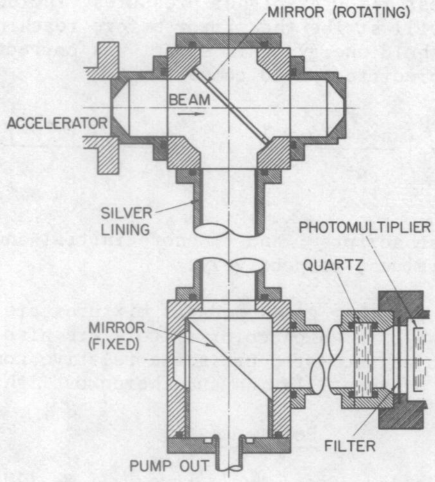


Fig. 1. Gas Cherenkov detector system used in the electron accelerator experiments.

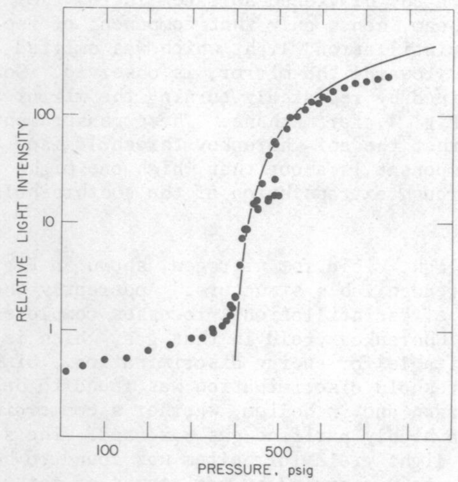
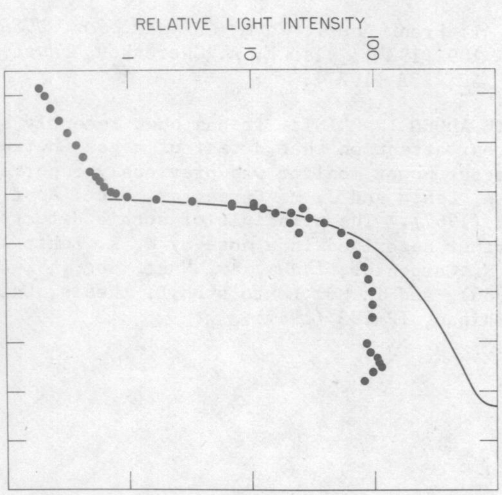


Fig. 3. Resumé of the light yield data for ethane from the Van de Graaff experiments. The smooth curve is the calculated Cherenkov light yield obtained from the computer code CHERY.

Fig. 2. Resumé of light yield data for methane from the Van de Graaff experiments. The smooth curve is the calculated Cherenkov light yield obtained from the computer code CHERY.



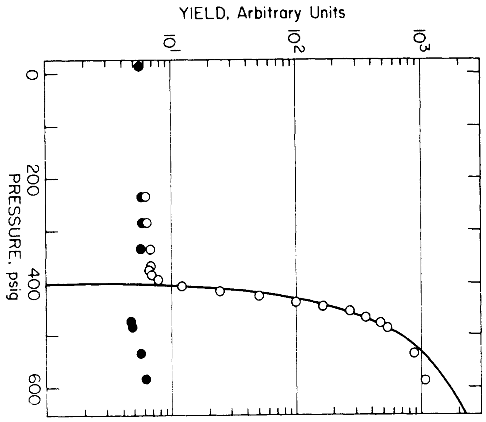


Fig. 4. Light yield data for methane with turning mirror. Open circles indicate mirror viewing front part of detector, solid circles indicate mirror viewing back part of detector, and smooth curve indicates computed light yield.

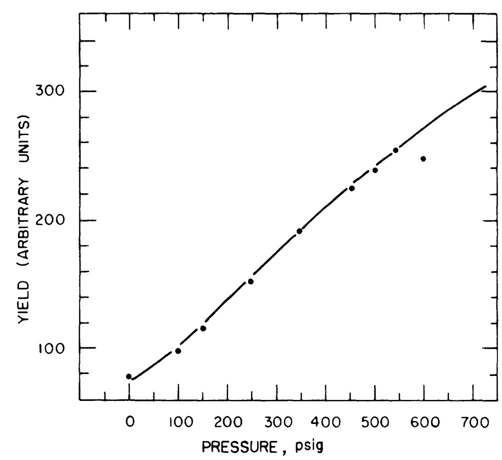


Fig. 5. Light yield data for nitrogen obtained with 3-MeV Van de Graaff electrons.

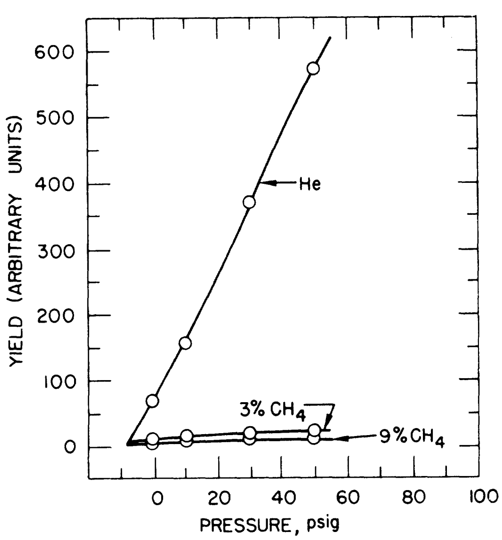


Fig. 6. Light yield data from the Van de Graaff experiments for high-purity helium, helium with 3% methane, and helium with 9% methane.