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CALCULATED TIME-CORRELATED
NEUTRON-INDUCED RADIATIONS
IN A SANDSTONE FORMATION

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C.W. PETERS AND E.I. KARAOGLAN

PREPARED FOR:

BENDIX FIELD ENGINEERING CORPORATION
Grand Junction Operations
Grand Junction, Colorado 81501

950 9681
(CONSOLIDATED CONTROLS CORPORATION
7213 Lockport Place
P. O. Box 726
Springfield, Virginia 22150

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1. INTRODUCTION

The Grand Junction Operations Office, Department of Energy, via its contractor, The Bendix Field Engineering Corporation, is developing technologies to explore for uranium as a part of the National Uranium Resource Evaluation (NURE) Program. This report is addressed to the potential use of the associated particle technique¹ for spatially and temporally correlating the detected radiations from events induced in the borehole and the formation by neutrons with the time and the direction that the neutrons are emitted.

An energetic (14 MeV) neutron can induce a large variety of radiations in a medium. Chronologically, from the time of emission from the source, the most probable types of these events include:

- (1) very fast (10^{-9} s) events from fast-neutron reactions, such as inelastic gamma rays and, less probable, gamma rays from charged particle interactions and fast-neutron fission
- (2) fast (10^{-5} s) events from slow neutron capture, such as capture gamma rays and, less likely, slow-neutron fission
- (3) slow (seconds to years) events from the decay of nuclei excited by one of the fast-neutron reactions or slow-neutron capture reactions.

The first two types of reactions usually produce high-energy gamma rays for most elements, which are desirable for borehole exploration because of their long mean free paths relative to decay gamma rays, which usually are low-energy gamma rays with a shorter mean free path. Consequently, the use of the associated particle technique to identify the detected radiation from the first two types of reactions by correlating their occurrence in time with neutron emission is expected to result in the design of a new borehole probe that may be more versatile and useful for uranium exploration than currently available probes.

The following Sections describe the use of the response equations, which are developed in Appendix A, to determine the potential design of a Borehole Neutron Diagnostic Probe and to calculate the responses of this probe design to a sandstone formation. The

measured responses of primary interest include:

- (1) the signal from the coincident detection of a prompt gamma ray and a prompt neutron, delayed by its travel time, from fast-neutron induced fission;
- (2) the time dependence of the inelastic-gamma ray signal;
- (3) the time dependence of the capture-gamma ray signal;
- (4) the capture-gamma ray spectrum and the detectability of H, O, Si, Cl, Ca, and V;
- (5) the inelastic-gamma ray spectrum and the detectability of C and O.

2. THE ASSOCIATED-PARTICLE TIME-CORRELATION TECHNIQUE

The proposed Borehole Diagnostic Neutron Probe uses the following reaction to generate neutrons.

The neutron production is monoenergetic, continuous, and isotropic in the center of mass system and very nearly isotropic in the laboratory system. The alpha particle is emitted at 180° from the direction of the emitted neutron. If an alpha detector is located on one side of the tritium target, then each detected alpha particle corresponds to a 14 MeV neutron emitted in the opposite direction and also corresponds to the time the neutron is emitted, with a correction for the time of flight from the target to the alpha detector.

If the deuteron beam is focused onto the tritium target, then the solid angle subtended by the alpha detector will correspond to the solid angle into which the neutrons, whose associated alpha particles are detected, are emitted. In the borehole geometry shown in Figure 1, this solid angle is chosen so that the neutrons that enter the formation along and around the axis of the borehole are monitored by the alpha detector.

The nuclear reactions from these neutrons in the formation are observed by a gamma ray and/or a neutron detector. The time between the emission of the 14 MeV neutron and the detection of a gamma ray from a subsequent interaction of the emitted neutron in the formation can be measured very accurately.

The emitted 14 MeV neutron will undergo from one to a large number of nuclear interactions in the formation. The total cross-section at each interaction is:

$$\sigma_T = \sigma_{el} + \sigma_{non-el}$$

Figure 1 Vertical Cross-Section of Borehole Neutron Diagnostic Probe to Illustrate Detection Geometry. Details of Probe and Associated Electronics are not shown. (n_0 -Initially Emitted Neutron; n_s -Scattered Neutron; γ_s -Scattered Gamma Ray; γ_c -Capture Gamma Ray)

where:

σ_{el} = elastic neutron scattering cross-section. In this interaction the neutron loses part of its energy depending upon the scattering angle and the mass (atomic number) of the scattering nucleus

σ_{non-el} = non-elastic neutron interaction cross-section.

The non-elastic cross-section is composed of the sum of several cross-sections, or;

$$(1) \quad \sigma_{non-el} = \sigma(n, \gamma_C) + \sigma(n, n' \gamma_I) + \sigma(n, 2n) + \sigma(n, X \gamma_R) + \sigma(n, f)$$

where: $\sigma(n, \gamma_C)$ = radiation capture cross-section

$\sigma(n, n' \gamma_I)$ = inelastic neutron scattering cross-section, in which one or more prompt gamma rays are emitted and a neutron with much less energy than the incident neutron is emitted

$\sigma(n, 2n)$ = $(n, 2n)$ cross-section in which two prompt neutrons with much less energy than the incident neutron are emitted

$\sigma(n, X \gamma_R)$ = charged particle reaction cross-section in which prompt reaction product gamma rays are emitted in many cases

$\sigma(n, f)$ = fission cross-section in which several prompt neutrons and several prompt gamma rays are emitted

The values of these cross-sections vary with the isotope and with the energy of the incident neutron. The number of prompt gamma rays and neutrons produced from fast neutron interactions

with a specific isotope usually varies with the energy of the neutron. Most of these reactions will leave the residual nucleus in an excited state and it may subsequently decay by gamma ray emission, however these delayed gamma rays are not expected to be observed (except as accidental background) by the proposed time of flight technique because their delay times are usually long compared to prompt gamma-ray emission (10^{-14} seconds or less).

The probability (P_i) that a neutron will interact with a specific isotope (i) is proportional to the product of the density of the isotope (n_i) and its total cross-section, or

$$P_i = n_i \sigma_{T_i} = n_i \{ \sigma_{el_i} + \sigma_{non-el_i} \}$$

The probability of a specific reaction will depend on the values of the various cross-sections.

In general, the elements in the most abundance to be found in borehole formations are expected to have low to intermediate mass numbers, i.e., atomic mass $A < 80$. For these elements, the predominant cross-sections for neutron energies above about 0.5 MeV are expected to be elastic scattering, σ_{el} , and inelastic scattering, $\sigma(n, n' \gamma_I)$; consequently equation (1) becomes:

$$\sigma_{non-el} \approx \sigma(n, n' \gamma_I)$$

At 14 MeV, the elastic scattering cross-section will be about equal to the inelastic scattering cross-section, which gradually decreases with decreasing neutron energy down to the threshold, typically at about 1-2 MeV. Between the threshold and epi-thermal energies (1-15 eV), the elastic scattering cross-section is predominant. The capture cross-section, $\sigma(n, \gamma_C)$, usually increases in the epi-thermal and thermal range. Hence, the capture and elastic scattering cross-sections are predominant in the epi-thermal and thermal neutron energy ranges.

From the above discussion, the emitted 14 MeV neutron will

travel with a velocity, v_1 , until it interacts at a distance, R_1 , with a nucleus in the borehole or in the formation. In general, the first interaction will be an elastic or an inelastic scatter with about equal probability. The first interaction will result in a scattered neutron with an energy less than 14 MeV, and the neutron will have a velocity $v_2 < v_1$ until it undergoes a second, similar interaction. As this process continues, the resulting neutron loses energy until it eventually reaches thermal equilibrium, unless one of the interactions absorbs the neutron. After the neutron reaches thermal energy, it continues to undergo elastic collisions with small gains and losses in energy until it is captured.

If the gamma ray production versus time for each emitted neutron is observed for a large number of neutrons, then a time spectrum such as that shown in Figure 2 will be obtained. It can be subdivided into three regions:

1. 14 MeV
2. slowing down
3. thermal.

The 14 MeV region primarily contains the inelastic gamma rays produced in the first interaction. The velocity of a 14 MeV neutron is 5.6 cm/ns. The time range of this region will be from 0 to about $R_1/5.6$, where R_1 is the mean free path for 14 MeV neutrons. For example, if R_1 is 11 cm then the 14 MeV region will be from 0 to $2 \cdot 10^{-9}$ s. The magnitude of the gamma ray production in this region is expected to depend upon the borehole conditions. If the borehole is dry, then the magnitude of the 14 MeV region will be low, and the inelastic gamma ray energy spectrum should be mainly due to interactions in the neutron generator casing. If the borehole is filled with water, then the magnitude should be higher and the inelastic gamma-ray spectrum should include interactions from oxygen in the water.

The slowing down region is expected to extend to about $5 \cdot 10^{-6}$ s. The gamma-ray production from 14 MeV to about 1 MeV versus time is related to the neutron slowing down time, which is sensitive to the hydrogen content of the formation. The average fractional

Figure 2 : Computed Neutron-Induced Gamma-Ray Production versus Time of Flight for a Pure Carbon Medium. (Calculated from Equations in Appendix)

energy lost by a fast neutron in an elastic collision increases as the mass of the nucleus decreases. Because of this effect, a 14 MeV neutron will require fewer elastic collisions to reach thermal energy in a formation with a high hydrogen content (e.g., water) than in the same formation with a low hydrogen content. Consequently, the time dependence of the slowing down portion of the prompt radiation from fast neutrons will be affected by the hydrogen content of the formation. The inelastic gamma-ray energy spectra produced during the first 10^{-8} seconds is expected to be characteristic of the type of elements and their abundance in the formation.²

Below 1 MeV, at about 10^{-8} seconds, the elastic scattering cross-section predominates until the neutrons have slowed down to epi-thermal energies, at about 10^{-6} s, after which the capture gamma-ray production increases reaching a peak at about $5 \cdot 10^{-6}$ s when the neutrons have reached thermal energies.

The thermal region extends from about 10^{-6} s to about 10^{-4} s. After the neutrons reach thermal equilibrium at about $5 \cdot 10^{-6}$ s they die away at a constant rate proportional to the thermal macroscopic absorption cross-section. The capture-gamma-ray spectrum is expected to be characteristic of the elements and their abundance in the formation.²

The above discussion of the expected time spectrum of prompt radiation from fast neutrons is based on the observation that most (e.g., 99%) of the interactions will be elastic or inelastic scattering for the isotopic abundances expected to be found in borehole formations.

The primary influence of variations in the abundance of isotopes such as ^{10}B , ^6Li , and ^{235}U , on the shape of the time distribution of prompt radiation will be in their contributions to the thermal neutron macroscopic absorption cross-section which governs the die-away time of the thermal neutrons.

The principles of neutron transport and diffusion theory were used to develop equations for modeling the response of the system to inelastic-gamma ray, capture-gamma ray, and fission prompt-gamma ray/prompt-neutron radiations. The development of these equations is described in Appendix A.

3. APPLICATION TO A SANDSTONE FORMATION

The results of the use of the equations in Appendix A to determine the design features of a borehole probe using the associated-particle time-of-flight technique in a sandstone formation is discussed in this section.

3.1 FORMATION AND BOREHOLE CHARACTERISTICS

The example chosen for calculational purposes is a 2.5 inch diameter probe in a 4.5 inch diameter borehole, dry and water-filled, in a sandstone formation containing 13% water and 0.1% natural uranium accompanied by 1% vanadium. The probe-borehole geometry is illustrated in Figure 3. The physical characteristics and the calculated neutron transport terms of the formation are tabulated in Appendix A.

3.2 DETECTOR DESIGN

The desired measurements from the detector are:

1. the energy spectrum of inelastic-gamma rays, which are produced by fast neutron interactions
2. the energy spectrum of capture-gamma rays, which are produced by thermal neutron capture
3. coincidences between prompt-gamma rays and prompt-neutrons, which are produced by fast-neutron fission (^{238}U) or thermal-neutron fission (^{235}U)
4. the time dependence of the inelastic-gamma ray signal
5. the time dependence of the capture-gamma ray signal.

The above measurements will be influenced by variations in borehole and/or formation parameters. An estimate of these variations, deduced from the above measurements, is desired in order to:

1. determine formation parameters of geophysical significance and/or;
2. determine corrections to the above measurements.

The capability of the system to make the above measurements and

Figure 3 Probe-Borehole Geometry

to estimate variations in borehole and/or formation parameters will depend upon the type of detector, the geometrical design of the probe, and the design of the electronics.

In general, the advantage of detecting inelastic and/or capture gamma radiation over detecting decay gamma radiation is that inelastic and capture gamma rays usually are high-energy gamma rays, e.g., greater than 2 MeV, that have a longer mean free path in the formation than that of the lower energy gamma rays, e.g., less than 2 MeV, from gamma ray decay. This advantage is illustrated by Figure 4, which shows the calculated variation of the gamma-ray attenuation coefficient versus gamma-ray energy for the sandstone formation. The inelastic and capture gamma ray production spectra for most elements contains several energy lines ranging up to 8 MeV. The gamma ray flux incident on the detector will consist of those discrete gamma ray energies transmitted through the formation plus a Compton continuum of gamma rays scattered by the formation. The resulting spectrum detected by a gamma ray spectrometer will consist of photopeaks from the discrete gamma ray energy lines to about 8 MeV superimposed on a Compton continuum that is very large near 0.1 MeV and decreases rapidly with energy to about 1 MeV. For a formation containing many elements, there will usually be a number of small photopeaks below about 1 MeV. Also, most of the background gamma-ray spectrum from natural radioactivity and decay gamma radiation will be below about 2 MeV. Consequently, the region of the gamma ray spectrum below about 1 MeV will be very difficult to analyze, and the region above 1 MeV will be of the most practical interest.

The most abundant element characteristic to sandstone is silicon which produces a prominent inelastic gamma-ray at 1.78 MeV and prominent capture gamma-rays at 4.75 and 3.54 MeV. The variations in the intensity of these gamma rays from silicon is expected to be representative of the gamma rays of interest and was studied to determine some of the detector parameters. The inverse neutron spectrum stripping technique³ was used to calculate the variation of the primary silicon gamma ray intensities versus distance from the 14 MeV neutron source. This is shown in Figure 5 for inelastic and

Figure 4 Variation of Gamma-Ray Attenuation Coefficient versus Gamma-Ray Energy for a Sandstone Formation.

capture events and for 0 percent and 22 percent water content in the sandstone formation around a dry borehole. The influence of adding water to the borehole resulted in a reduction of less than 5 percent of the intensities shown in Figure 5. Consequently, the presence of water in a 4.5 inch borehole around a 2.5 inch diameter probe has only a small influence on the magnitudes of the discrete inelastic and capture gamma ray lines with energies above about 1 MeV that are incident on the probe.

The effect of changing the angle, θ , of the cone of alpha-particle-associated neutrons on the intensity of the primary inelastic and capture gamma rays from silicon versus distance from the neutron source is shown in Figure 6. The change in angle produces a significant change in the intensity of the incident inelastic gamma rays. The maximum angle for efficient detection of the associated alpha particle is estimated to be about $\theta = 60^\circ$ (Figure 3); at larger angles more than about 20 percent of the alpha particle energy may be lost in the tritium target. Decreasing the angle below 60° will reduce the intensity of the time correlated fast neutron events and increase the background from uncorrelated fast neutron events. This effect is much less significant for capture gamma rays than for inelastic gamma rays as shown in Figure 6.

The time dependence of the silicon inelastic and capture gamma radiation incident on the probe is shown in Figures 7 and 8 for different water contents in a sandstone formation.

Figure 7 shows that the time dependence of inelastic gamma radiation is very sensitive to water concentration in a sandstone formation.

From Figure 8, the use of the associated particle time-of-flight technique to observe the capture gamma-ray events will require delay times between successive neutron emissions of about 10^{-4} seconds, which will require the neutron source output to be lowered to about 10^4 n/s and drastically reduce the detection capability of the probe. A practical method of measuring the time dependence of the capture gamma rays without lowering the neutron output has not been conceived. Consequently, the remainder of

Figure 5 Intensity of the Unscattered Silicon Gamma Rays Incident on a 2.5 Inch Diameter Detector Versus Distance from a 14 MeV Neutron Source for 0% and 22% Water Concentration in a Sandstone Formation.

Figure 6 Intensity of the Unscattered Silicon Gamma Rays Incident on a 2.5 Inch Diameter Detector Versus Distance from a 14 MeV Neutron Source for Different θ Values in a Sandstone Formation with 13% Water

Figure 7 Time Dependence of the Silicon Inelastic Gamma-Rays in the Sandstone Formation for Different Water Concentrations. Time is Measured in Nanoseconds (10^{-9}s) from the Emission of a Neutron from the Neutron Generator to the Arrival of the Gamma Ray at the Detector.

Figure 8 Time Dependence of the Silicon Capture Gamma-Rays in the Sandstone Formation for Different Water Concentrations. Time is measured in microseconds.

this report is addressed to time correlation of the fast neutron events only.

The desired probe will contain:

1. a gamma ray spectrometer for inelastic and capture gamma rays
2. a time of flight spectrometer for inelastic gamma rays
3. a prompt gamma ray/prompt neutron coincidence detector of fission events.

Potential detector types include:

1. Organic Scintillators, such as NE102, which are sensitive to prompt neutrons and gamma rays with a fast time response desirable for fast timing, e.g., 10^{-9} s, but which are very poor for use in gamma ray spectrometers.
2. Inorganic Scintillators, such as NaI which are very sensitive to gamma rays, but are insensitive to prompt neutrons, are poor for fast timing less than about 10^{-6} seconds, and have a moderate resolution for spectrometry.
3. Solid State Detectors, such as Ge(Li), which are excellent for use in spectrometers and have good fast timing characteristics, but have very low sensitivity to high energy gamma rays above about 1 MeV, are insensitive to neutrons, and require cryogenic cooling.
4. A combination of the above, such as a NaI or Ge(Li) gamma ray spectrometer and an organic scintillator for neutron detection and fast timing.
5. An anti-Compton spectrometer consisting of a NaI or Ge(Li) detector surrounded by an organic scintillator, which is used in this application to (a) detect coincidence events from prompt

neutrons and prompt gammas in the organic scintillator, (b) to observe the gamma ray spectra in the NaI or Ge(Li) detector, and (c) to improve the spectral characteristics by eliminating gamma ray events occurring in both detectors such as Compton scattered and escape gamma rays.

The approximate response of a detector composed of a NaI crystal inside a cylinder of NE102 plastic scintillator to 4.4 MeV gamma rays incident on the detector is shown in Figure 9 as a function of the diameter of the NaI. The NaI curve is the 4.4 MeV photopeak response. The double escape curve is the response of the NE102 to two 0.511 MeV escape gamma rays from pair production in the NaI. The coincidence curve is the response of the NE102 to prompt neutron and prompt gamma-ray coincidences from fission.

The response of a solid state detector, e.g., Ge(Li), would be lower than the NaI response by a factor of 10 or more and would require cryogenic cooling, hence a solid state detector is considered less desirable than a NaI detector.

If the detector is to be an anti-Compton detector that is about equally effective as a gamma-ray spectrometer, a fission coincidence detector, and a fast time-of-flight spectrometer, then a NaI diameter of 3 cm with an NE102 thickness of about 1 cm is about optimum, as seen from the intersection of the curves in Figure 9.

A number of alternative detector designs can be identified from the relative responses shown in Figure 9 and from the distribution of fast and slow neutron events as a function of distance from the neutron source shown in Figure 5. The fast-neutron induced events can be distinguished from slow-neutron events by time correlation with the associated alpha particle and/or by selecting the length of the detector and its location relative to the neutron source so as to be optimum for the desired response.

Some of these alternatives include:

1. A long anti-Compton detector as discussed above to simultaneously detect the fission coincidence signal, inelastic gamma rays, and capture gamma rays

Figure 9 Approximate Response of a 5 cm Diameter Detector Composed of a NaI Cylinder Enclosed in a Cylinder of NE102 Scintillator versus Diameter of the NaI for 4.4 MeV Gamma Rays.

2. Two anti-Compton detectors as above but each about 30 cm long and positioned such that the one closest to the neutron source is most sensitive to fast neutron events and the other is most sensitive to thermal neutron events. (This configuration requires duplicate sets of electronics which will be more costly than the first alternative.)
3. Three detectors, the first (closest to the neutron source), an all plastic scintillator to observe the fast neutron induced fission coincidence signal, the second, a NaI spectrometer to observe the inelastic and capture gamma ray spectra, and the third, a plastic scintillator to observe the thermal fission induced coincidence signal. (This configuration is optimized towards the measurement of the fission coincidence signal at the expense of reducing the gamma-ray spectral sensitivity.)
4. Three detectors, the first, a NaI spectrometer, the second, a plastic scintillator, and the third, a NaI spectrometer. (This configuration is optimized towards the measurement of the inelastic and capture gamma-ray spectra at the expense of reducing the fission coincidence signal.)
5. A long NaI spectrometer, which will not be capable of observing the time dependence of the fast neutron events or the fission coincidence signal
6. A long plastic scintillator, which will not be capable of observing the inelastic and capture gamma ray spectra.

On the basis of minimizing costs and maximizing the quantity of useful information, the first alternative is believed to be the most desirable for uranium exploration.

The time dependence of the inelastic gamma ray signal shown in Figure 7 indicates that the fast neutron events can be separated from most of the other events by gates with gate-times of about 10^{-8} seconds that are started at the time of emission of an alpha

particle. The desired length of the anti-Compton detector and its distance from the neutron generator is determined by its capability to detect gamma rays from fast and slow neutron events.

The detection capability of a radiation detection system is frequently defined as the ratio:

$$(2) \quad \text{det.cap.} = S/B^{1/2}$$

where: S = net signal, i.e., background subtracted,
in counts for a measurement time, t_m

B = background in counts per t_m

t_m = measurement time

This expression comes from the definition of minimum detectable level (MDL), which may be derived as follows. If B is the background measured in a time, t_m , then the true background, B_{true} , is:

$$B_{\text{true}} = B \pm k B^{1/2}$$

where: k = precision in units of sigma

If a second measurement is made in a measurement time, t_m , with a small signal, S , believed to be present, then the total measured signal, $S + B$, must be greater than the maximum expected value of B_{true} (which is $B + kB^{1/2}$) if the signal, S , is detectable, i.e.;

$$(3) \quad S + B \geq B + kB^{1/2}$$

or:

$$S \geq kB^{1/2}$$

or:

$$S/B^{1/2} \geq k$$

The ratio, $S/B^{1/2}$, is useful for comparing the detection capability of two different measurement systems.

The MDL is obtained by setting:

$$S = kB^{\frac{1}{2}}$$

and by substituting:

$$S = R \cdot (\text{MDL})$$

where:

R = signal per unit quantity of the substance
to be measured

(MDL) = minimum detectable level in units of the
quantity of substance to be measured
(e.g., curies, gms, etc.)

to yield:

$$(\text{MDL}) = kB^{\frac{1}{2}}/R$$

Usually, k is set equal to 3, to provide the confidence level
associated with 3 sigma or

$$(4) \quad \text{MDL} = 3B^{\frac{1}{2}}/R$$

For the case of the slow neutron induced events, the desired
signal is the capture gamma-ray signal:

$$S_c(E) = S_c^C(E) + S_c^{F.S.}(E)$$

where:

$S_c^C(E)$ = Signal from capture gamma rays that is
transmitted through the formation,
which is a line spectrum.

$S_c^{F.S.}$ = Signal from capture gamma rays that is
scattered in the formation, which is a
Compton continuum below about 2 MeV with
an intensity about equal to that of the
signal $S_c^C(E)$

The background to this signal, with those fast events correlated with alpha detection gated out, will be:

$$B_c = B_{\text{nat}} + B_F(\theta < 5^\circ) + B_F(\theta > 60^\circ) + B_{\text{decay}}$$

where:

B_{nat} = Signal from gamma radiation from natural radioactivity, most of which will be less than 1 MeV and will vary directly with length, L_d , of the detector.

$B_F(\theta < 5^\circ)$ = Signal from fast neutron events produced by neutrons emitted in the 5° cone subtended by the detector that is not associated with detected alpha particles, which is estimated to be about 600 c/s for a source strength of 10^7 n/s from (n,n' γ) scattering at 14 MeV in the NaI and is nearly independent of the length or location of the NaI detector.

$B_F(\theta > 60^\circ)$ = Signal from fast neutron events produced by neutrons emitted outside the 60° cone, which is estimated on the basis of solid angle and attenuation to vary as $3.5 \cdot 10^3 / L_1^2$ c/s for 10^7 n/s, where L_1 is the distance from the end of the detector to the neutron source. $B_F(\theta > 60^\circ)$ is not significant for $L_1 > 10$ cm.

B_{decay} = Signal from neutron events in the formation that decay by emitting gamma rays. B_{decay} is small relative to other signals, and the gamma rays have energies less than about 3 MeV.

To a first approximation, the capture gamma ray detection capability can be represented as:

$$S_c / (B_C)^{1/2} \approx S_c / (B_{nat})^{1/2}$$

where:

B_C = Background to capture gamma ray signal S_c

$B_C \approx B_{nat}$, neglecting other backgrounds, as discussed above.

The natural background will vary with the length, L_d , of the detector, or

$$B_{nat} \approx k L_d$$

The constant, k , was calculated to be about 60 c/s per centimeter for a 3 cm diameter NaI detector from experimental data provided by BFEC for a NaI detector in a sandstone formation containing about 0.08 percent U, consequently:

$$B_{nat} \approx 60 L_d$$

If the center of the detector is located equidistant between the inelastic and capture gamma ray distribution shown in Figure 5, or at about 32.5 cm, then the capture gamma ray detection capability as a function of L_d will increase to a maximum at $L_d \approx 45$ cm.

For the case of the time-correlated fast-neutron events, the desired spectral signal is:

$$S_I(E) = S_I^I(E) + S_I^F \cdot S_c(E)$$

where:

$S_I(E)$ = Inelastic gamma-ray signal

$S_I^I(E)$ = Signal from inelastic gamma-rays not scattered in the formation

$$S_I^{F.S.}(E) = \text{Signal from formation scattered inelastic gamma rays}$$

The background to the inelastic-gamma ray signal, $S_I(E)$, is designated, B_I , and it will be from those gamma rays that are accidentally detected in coincidence with the alpha detector pulses, or:

$$B_I \approx B_{acc}$$

For a gate time, $T_g = 10^{-8}$ s, (i.e., a coincidence resolving time of $5 \cdot 10^{-9}$ s), the accidental background will be:

$$B_{acc} = T_g C_a B_F$$

where C_a is the alpha particle count rate, which is:

$C_a = 10^7/4$ c/s for a 10^7 n/s source and the solid angle defined by the 60° cone, and:

$$B_{acc} = 10^{-8} 10^7 B_F / 4 = B_F / 40$$

where; B_F is the sum of all signals not correlated with the detection of an alpha particle, i.e.,

$$B_F = S_c^c + S_c^{F.S.} + B_{nat} + B \text{ (other backgrounds)}$$

and, neglecting the "other" backgrounds, the inelastic gamma ray detection capability is:

$$\begin{aligned} S_I / B_I^{1/2} &= S_I / B_{acc}^{1/2} \\ &= S_I / (B_F / 40)^{1/2} \\ &\approx S_I / \{(S_c^c + S_c^{F.S.} + B_{nat}) / 40\}^{1/2} \\ &= S_I / \{(S_c + B_{nat}) / 40\}^{1/2} \end{aligned}$$

If the center of the detector is located equidistant between the inelastic and capture gamma ray distributions, as shown in Figure 5, or at about 32.5 cm, then the inelastic gamma-ray detection capability as a function of L_d will increase to a maximum at $L_d = 45$ cm.

In the above discussion, the end of the detector is about 10 cm from the neutron source. If the end is moved closer to the neutron source, then the background from inelastic events for $\theta > 60^\circ$ will begin to increase the magnitude of the backgrounds for both inelastic and capture gamma ray signals.

From the above discussion, two anti-Compton detectors, one optimized for the inelastic events and the other optimized for capture events will improve the respective detection capabilities. However, such a probe would double the cost of the detector and associated electronics.

Summary

From the above discussion, the following probe characteristics have been selected:

$$N = 10^7 \text{ n/s} = \text{neutron generator output}$$

$$\theta = 60^\circ = \text{angle of cone subtended by the alpha detector and also the angle of the cone of emitted neutrons that are used for time correlation}$$

$$\begin{aligned} C_a &= N/4 = \text{average count rate of the alpha detector} \\ &= 2.5 \cdot 10^6 \text{ c/s} \end{aligned}$$

Detector Type: An anti-Compton gamma-ray spectrometer, consisting of a NaI(Tl) scintillator enclosed by an NE102 plastic scintillator

o.d._{NaI} = 3 cm = outside diameter of the NaI scintillator

o.d._{NE102} = 5 cm = outside diameter of NE102 scintillator

i.d._{NE102} = 3 cm = inside diameter of NE102 scintillator

o.d._{probe} = 2.5 inches = 6.35 cm = outside diameter of probe

L_d = 45 cm = length of scintillators

L_1 = 10 cm = distance from neutron source to the
closest end of scintillator

L_2 = 55 cm = distance from neutron source to the
furthest end of scintillator

If C_p and C_g are used to denote the signals from the plastic (NE102) and the gamma ray spectrometer (NaI), respectively; then:

$$S_I = C_p^I \text{ or } C_g^I = \text{counts correlated with } C_a$$

$$S_c = C_p^c \text{ or } C_g^c = \text{counts not correlated with } C_a$$

3.3 FUNCTIONAL DETECTOR ELECTRONICS

A functional diagram of the detector electronics is shown in Figure 10. The coincidence outputs of the NaI and the NE102 detectors are used to gate these events out of the train of pulses from the NaI detector, i.e., the anti-Compton feature, leaving the signal:

$$C_g(E) = C_g^I(E) + C_g^c(E)$$

where $C_g^I(E)$ are the events correlated with the alpha detector output, C_a , and $C_g^c(E)$ are the non-correlated events. Coincidences with the C_a signal select the $C_g^I(E)$ spectrum for storage in a multichannel analyzer (MCA). The NaI pulses not in coinci-

Figure 10 Functional Block Diagram of Electronics for the Neutron Diagnostic Probe.

dence with C_a pulses are stored in the $C_g^C(E)$ MCA. This spectrum contains the capture gamma ray spectrum, i.e.,

$$S_c^C(E) + S_c^{F.S.}(E) + B_{nat} + B(\text{other})$$

The NE102 plastic scintillator output contains pulses from time correlated events and other events, i.e.,

$$C_p = C_p^I + C_p^C$$

If the outputs of the alpha detector, C_a , and the NE102, C_p , are used to drive a time to amplitude convertor (TAC) and the resulting time dependence is stored in an MCA, then the time dependence of the inelastic gamma events, $C_p^I(\text{TOF})$, superimposed on a random accidental background, $T_1 C_a C_p^C$, will be observed. For the

case $T_1 = 10^{-9}$ s and $C_a = 2.5 \cdot 10^6$, the random accidental background will be: $C_p^C/400$.

If the train of pulses from the NE102 are used to drive a TAC, whose start pulses are delayed by a few ns, then this TAC output will contain the time spectrum of time intervals between pulses superimposed on a random accidental background ($T_1 C_p^2$).

The NE102 will be sensitive to prompt neutrons and to prompt gamma rays from fission. On the average, the difference in arrival times at the NE102 between a prompt neutron and a prompt gamma ray from fission will be

$$\begin{aligned} t &= r_2/V_n - r_2/V_g \\ &= r_2(1/1.4 - 1/30) \text{ ns} \end{aligned}$$

where:

$$V_n = 1.4 \text{ cm/ns for a prompt fission neutron}$$

$$V_g = 30 \text{ cm/ns for a gamma ray}$$

The difference in arrival times of these fission events is expected to be minimum at about 3 ns, increase to a maximum at about 10 ns, and decrease rapidly with a long tail out to about 50 ns, with most of the fission events occurring within about 3 to 15 ns. Consequently this TAC could be replaced with a coincidence circuit as shown in Figure 10. The fast-neutron induced coincidences can be separated from the output of this fission coincidence circuit (or TAC) by requiring a coincidence between this circuit and the alpha detector output, C_a , as illustrated in Figure 10.

4. METHOD OF CALCULATING SIGNALS

The variety of signals observed by the NE102, the NaI, and in coincidence in both detectors is illustrated by Table 1. Several signals, such as backscattering of gamma rays out of the detector, the 0.5 MeV annihilation peak, etc., were neglected because of their small magnitude and because their energies fall in the less than 1 MeV region, which is considered to be a very difficult spectral analysis region. Table 1 is divided into two parts; radiations not correlated and radiations correlated within 10^{-8} s of the detection of an alpha particle associated with the emission of a 14 MeV source neutron in the $50^\circ < \theta < 60^\circ$ cone.

The natural background signal was estimated from an experimental natural background spectrum supplied by BFEC for a probe in a sandstone formation containing 0.08 percent uranium. The other signals were computed as follows. The incident radiation spectra were calculated from the equations in the Appendix for the sandstone formation characterized by Tables 3 through 5 in the Appendix and the probe-detector characteristics defined in Section 3. The fraction of the incident radiation detected by the NE102 was subtracted from the incident radiation intensity and the spectrum detected by the NaI was calculated. The NaI spectrum was corrected for the events eliminated by the anti-Compton feature. The anti-Compton corrected spectra for each incident radiation were summed to give the spectral output, $C_g^I(E) + C_g^C(E)$, of the NaI spectrometer. The types of incident radiation detected by the NE102 were integrated over gamma-ray energy and were summed to yield the NE102 count rate; $C_p^I + C_p^C$.

Because of the difficulty of calculating the spectra (Compton continuum) of the incident gamma-ray radiations that are scattered in the formation, these spectra were estimated by assuming that the magnitude of the incident formation scattered radiation intensities integrated over energy was equal to the magnitude of the associated incident transmitted (line spectra) radiation intensities summed over energy.

TABLE 1

SOURCE OF SIGNALS OBSERVED BY ANTI-COMPTON DETECTOR

RADIATION INCIDENT ON PROBE	SIGNIFICANT EVENTS OBSERVED BY:		
	NE102	BOTH	NaI SPECTRO- METER
A. Radiations Not Time Correlated (10^{-8} s) with C_a			
A-1 Capture Gamma Rays (line spectrum) Transmitted Through Formation	Compton Scattering	Compton & Escape Gammas	Capture Gamma Ray Spectrum
A-2 Capture Gamma Rays Scattered in Formation (Compton continuum)	do.	do.	Formation Scat- tered Capture Gamma Ray Spectrum
A-3 Background From Natural Radio- activity in Formation	do.	do.	Natural Gamma Ray Spectrum
A-4 Background From 14 MeV Neutrons in $\theta < 5^\circ$ Cone on End of Probe	14 MeV Neu- tron Elastic Scattering	do.	Inelastic Gamma Ray Spectrum of 14 MeV Neutrons on NaI
A-5 Prompt Neutrons & Gamma Rays From Thermal Fission	Prompt Neu- tron & Gamma Scattering	do.	Prompt Fission Gamma Ray Spectrum
A-6 Background From Neutron-Induced Decay Gamma Rays	do.	do.	Decay Gamma-Ray Spectrum
A-7 Background from Slow Neutron Capture in NaI	do.	do.	Capture Gamma Ray Spectrum for NaI
A-8 Background from Fast Neutrons For $\theta > 60^\circ$	do.	do.	Inelastic Gamma Ray Spectrum for Formation
A - SUB-TOTAL	C_p^c	NA	$C_g^c(E)$

TABLE 1 - CONTINUED

RADIATION INCIDENT ON PROBE	SIGNIFICANT EVENTS OBSERVED BY:		
	NE102	BOTH	NaI SPECTRO- METER
B. Radiation Time Cor- related (10^{-8} s) with C_a			
B-1 Inelastic Gamma Rays (line spectrum) Trans- mitted Through Formation	Compton Scattering	Compton & Escape Gammas	Inelastic Gamma Ray Spectrum
B-2 Inelastic Gamma Rays Scattered in Forma- tion (Compton contin- uum)	do.	do.	Formation Scat- tered Inelastic Gamma Ray Spectrum
B-3 Background From Source Neutrons Scattered in Formation	Neutron Elastic Scattering	do.	Inelastic Gamma Ray Spectrum of NaI
B-4 Prompt Neutrons and Gamma Rays From Fast Fission	Prompt Neu- tron & Gamma Ray Scattering	do.	Prompt Fission Gamma Ray Spectrum
B-5 Background From Acci- dental 10^{-8} s Coinci- dences	$10^{-8} C_a C_p^c$	NA	$10^{-8} C_a C_g^c(E)$
B - SUB-TOTAL	C_p^I	NA	$C_g^I(E)$
TOTAL	$C_p^I + C_p^c$	NA	$C_g^I(E) + C_g^c(E)$

5. SPATIAL RESOLUTION

The cone of 14 MeV neutrons emitted from the source is defined by the solid angle subtended by the alpha detector, which detects the alpha particle associated with the emission of a 14 MeV neutron. This alpha detector, which is a disc with a hole in the center to permit passage of the deuteron beam, could be subdivided into sections, e.g., quadrants, to spatially correlate the inelastic gamma ray spectrum, the fast neutron fission coincidence signal, and/or the time dependent inelastic gamma-ray signal with angle about the axis of the probe. This type of correlation might be useful for studying the variation of the formation around the borehole. For example, the response of a probe without any angular correlation is an average of the responses from different angles. A probe with angular correlation would give a better measurement of the uranium concentration, for example, if the uranium were situated on one side of the borehole.

The alpha detector could also be divided into rings to spatially correlate the fast neutron induced events that occur in the formation within a nested set of cones. The responses from these cones could be used to explore variations in the formation as a function of distance from the axis of the probe. As the probe is raised in the borehole, changes in the responses at the edge of a formation could be related to the tilt of the formation.

Although the concept of spatial resolution appears to be novel, its usefulness versus its added cost does not appear to be promising for use in uranium borehole logging.

6. CALCULATED RESPONSES

6.1 CAPTURE GAMMA RAY SPECTRAL RESPONSE

The calculated spectral signal not correlated with C_a counts, i.e., $C_g^c(E)$, measured by the NaI spectrometer in the 2.5 inch diameter probe discussed in Sections 3 and 4 for the sandstone formation with 0.1 percent natural uranium and 13 percent water content is shown in Figure 11. (This spectrum is similar to the experimental spectrum observed by Brafman².) The background, B_g , to the capture gamma ray spectral signal and its significant components are shown in Figure 12. The net capture gamma ray spectrum $C_g^c(E)$ is shown in Figure 13.

About 20 percent of the events detected by the NaI are eliminated by the anti-Compton gate, leaving about $1.5 \cdot 10^4$ c/s in the non-time correlated signal $C_g^c(E)$, from the NaI anti-Compton spectrometer, shown in Figure 11. The most prominent features of this signal are the large number of counts below about 1 MeV from the sum of the Compton continuum and the natural background and the photopeaks at 4.95, 4.44, 3.54, 2.78, 2.1, and 1.275 MeV from silicon in the formation. These photopeaks, together with those in the time-correlated spectral signal, could be used to identify the formation as sandstone. In order to identify elements less abundant than silicon in the formation, corrections must be made for the background shown in Figure 12. An important background correction is subtraction of the contribution from natural radioactivity in the formation. This background could be measured prior to turning the neutron generator on. However, this mode of operation requires a measurement at a fixed location in the borehole, rather than the scanning mode of operation normally employed in borehole logging. The background labeled, "others", in Figure 12, is the sum of the calculated backgrounds from;

1. ^{14}MeV neutrons in the $\theta < 5^\circ$ cone
2. Neutron-induced decay gamma rays
3. Slow neutron capture in the NaI
4. Fast neutron interactions for $\theta > 60^\circ$

This "other" background can be neglected because it is small and most of the photopeak structure is below 1 MeV.

The estimated non-time-correlated NaI spectrometer signal corrected for natural background is shown in Figure 13. (This spectrum is similar to the experimental spectrum observed by Brafman².) The most prominent features of this spectrum are the large capture gamma ray photopeaks from silicon plus a number of smaller photopeaks superimposed on the Compton continuum.

Since the silicon family of photopeaks is well known, the silicon response, normalized to the photopeak at 4.95 MeV, can be precisely subtracted from the spectrum shown in Figure 13 to yield the spectrum shown in Figure 14. The background and silicon corrected capture gamma ray spectrum shown in Figure 14 consists of a number of small photopeaks superimposed on a Compton continuum. These small capture gamma photopeaks could be used to identify hydrogen (at 2.23 MeV), calcium (at 5.25, 5.8, and 1.95 MeV) and vanadium (at 7.2 MeV).

For a sandstone formation, a reasonably precise measurement of the photopeak response of the NaI anti-Compton spectrometer to silicon can be made in a few seconds, and to hydrogen (22 percent water content) in about 10 seconds. Consequently silicon and hydrogen (at high water concentrations) could be measured at scanning velocities. However, precise measurements of these and other photopeaks will require background correction and/or measurement times ranging from 100 to 1,000 seconds, which will require very slow scanning speeds or measurement at a fixed location in the borehole.

Figure 11 Calculated Non-Time-Correlated Capture Gamma-Ray
 Response for the Spectrometer Discussed in Text.
 Peaks Not Labeled are Contributions from: Na, K,
 Ca, Al, and Mg Present in Sandstone.

Figure 12 Calculated Non-Time-Correlated Capture Gamma-Ray Background and its Components for the Spectrometer Discussed in Text

Figure 13   Calculated Non-Time-Correlated Capture Gamma-Ray
Spectrum for the Spectrometer Discussed in Text
After Subtraction of Natural Background

Figure 14 Calculated Non-Time-Correlated Capture Gamma-Ray Spectrum Measured by the Spectrometer Discussed in Text after Subtraction of Natural Background and Silicon Spectrum. Only the Gamma Rays of Interest in the Immediate Study are Labeled.

6.2 INELASTIC GAMMA RAY RESPONSE

A calculated spectral signal correlated by a 10^{-8} s gate with C_a counts, i.e., $C_g^I(E)$, measured by the gamma-ray anti-Compton spectrometer in the sandstone formation is shown in Figure 15. The $C_g^I(E)$ count rate is about $5.25 \cdot 10^3$ c/s.

The prominent features of this spectrum are photopeaks from silicon (1.78 MeV) and oxygen (6.1, 5.6, and 5.2 MeV) plus small photopeaks from aluminum and other elements superimposed upon the accidental background from non-time-correlated events. This accidental background from non-time-correlated events is

$$t_g C_a C_g^c(E) = C_g^c(E)/40$$

where: $t_g = 10^{-9}$ s

$$C_a = 10^7/4 \text{ c/s}$$

$C_g^c(E)$ = non-time-correlated spectrum in
Figure 11

Consequently, this accidental background can be easily subtracted from the time-correlated spectral signal to yield the inelastic gamma ray spectrum corrected for the accidental background as shown in Figure 16.

The prominent features of the background corrected inelastic gamma ray spectrum for sandstone are the photopeaks for oxygen, silicon, plus a number of smaller photopeaks from carbon, vanadium, calcium, aluminum, potassium, and other elements superimposed upon a Compton continuum.

The photopeak response for oxygen could be measured in a few seconds or at scanning velocity. However, precise measurement of the oxygen and other photopeaks will require very slow scanning velocities or measurements from 100 to 1,000 seconds at a fixed location in the borehole.

Conventional spectrum stripping techniques could be used to

Figure 15 Calculated Time-Correlated Inelastic Gamma-Ray Spectrum for the Spectrometer Discussed in Text

Figure 16   Calculated Time-Correlated Inelastic Gamma-Ray
 Spectrum after Background Subtraction for the
 Spectrometer Discussed in Text

Figure 17 Calculated Time-Correlated Inelastic Gamma-Ray Spectrum after Background Subtraction and Subtraction of Oxygen Spectrum for the Spectrometer Discussed in Text

Figure 18   Calculated Time-Correlated Inelastic Gamma-Ray
 Spectrum After Subtraction of Background, Oxygen,
 and Silicon Spectra for the Spectrometer Discussed
 in Text

sharply improve the measurement precision of the photopeaks. For example, removal of the oxygen spectrum normalized to the 6.1 MeV photopeak would improve the measurement of the carbon peaks as shown in Figure 17. Then removal of the silicon spectrum and of the carbon spectrum normalized to 4.44 MeV peak as shown in Figure 18 would improve the measurement of the calcium peaks at 3.65 and 3.9 MeV.

6.3 TIME DEPENDENCE OF INELASTIC GAMMA RAY RESPONSE

The output of the plastic (NE102) scintillator is

$$C_p = C_p^I + C_p^c$$

where: C_p^I = time correlated events with C_a .

C_p^c = non-time correlated events

and, for a 10^7 n/s neutron source;

$$C_p^I = 8.4 \cdot 10^3 \text{ c/s for sandstone with 13\% water}$$

$$C_p^c = 2.5 \cdot 10^4 \text{ c/s for sandstone with 13\% water}$$

The time dependence of the events detected by the NE102 scintillator correlated with the detection of an alpha particle, i.e., C_p^I , as measured by a time to amplitude convertor (TAC) is shown in Figure 19 for the sandstone formation with different water contents. The signal will be superimposed on the accidental count rate from non-time correlated pulses from the NE102 which will be:

$$C_p^I = T_1 C_a C_p^c = 60 \text{ c/s per ns}$$

where:

$$T_1 = 10^{-9} \text{ s}$$

$$C_a = 10^7/4 \text{ c/s}$$

$$C_p^c = 2.5 \cdot 10^4 \text{ c/s}$$

This accidental count rate could be estimated from the singles count rate from the NE102 pulses that are not coincident with C_a pulses.

The influence of the borehole geometry on the time dependent signal during the first 10^{-9} seconds is shown in Figure 19. If the borehole is dry, the count rate during the first 10^{-9} s will be low and from interactions in the probe. If the neutron generator is surrounded by water, the count rate during the first 10^{-9} s will increase slightly because of inelastic gamma rays from oxygen. The presence of water in a 4.5 inch borehole for a 2 inch diameter probe will have a negligibly small effect on the signal from the formation.

The time-correlated signal from 1 to 10 ns will vary with the water content of the formation as shown in Figure 20.

This response can be used to estimate the water concentration in the formation, which can be used to correct other responses that vary with water content.

6.4 TIME DEPENDENCE OF CAPTURE GAMMA RAY RESPONSE

If the system were designed such that the slow neutron events were correlated in time with C_a , then the estimate of the time dependence of the slow neutron events measured by the NE102 scintillator shown in Figure 21 would be observed for the sandstone formation with different water contents. The primary variation in this signal versus concentration of water in the formation is observed during the rise of the signal between about 10^{-6} and 10^{-5} seconds. Observation of this variation could be used to estimate the water content.

Figure 20 Variation of NE102 Time Correlated Events Between 1 ns and 10 ns with Water Concentration in the Formation

Figure 21 Calculated Time Dependence of Slow Neutron Events from NE102 Correlated with Alpha Particle Detection as Measured in TAC for Various H_2O Contents in this Formation

The decay time of this signal from its peak value is related to the thermal neutron mass absorption coefficient for the formation. Observation of the decay time (or the rise time) by the associated particle technique would require long TAC times and a low neutron emission rate from the neutron generator, which would drastically reduce the magnitude of the other signals.

6.5 PROMPT GAMMA/PROMPT NEUTRON COINCIDENCE RESPONSE FROM FISSION

The difference in travel time for prompt gamma rays and prompt neutrons from a fission event in the formation to the NE102 detector is estimated to range from about 3 ns to 30 ns with most of the events occurring between 3 ns and 15 ns. Consequently, if the output of the NE102 detector is divided into two identical outputs with one output delayed by about 2 ns and driving the "start" input of a coincidence circuit with a resolving time of 7 ns and the other output driving the "stop" input, then subsequent events that occur within 2 ns to 16 ns from each other in the NE102 will be counted as coincidences. The types of events observed will include fission events and accidental coincidences from the variety of random neutron and gamma ray events detected by the NE102. The signals observed will depend upon whether the fission events are from fast neutron or slow neutron fission.

6.5.1 COINCIDENCE SIGNAL FROM FAST-NEUTRON FISSION

The fast-fission coincidence signal can be separated from the slow-fission coincidence with the alpha detector pulses, C_a . The fast-fission coincidence signal from the detection of one or more prompt gamma rays and the subsequent detection of one or more prompt neutrons within 14 ns for a sandstone formation with 0.1 percent uranium and 13 percent water is calculated to be 11 coincidences/s (or 110 coincidences/s per percent of U). The average number of prompt neutrons per fast fission of ^{238}U is assumed to be 4 with an average energy of 1 MeV, and the average number of prompt gamma rays is assumed to be 8 with an average

energy of 0.9 MeV for this estimate.

The accidental coincidence rate, Co_{acc} , is estimated to be:

$$Co_{acc} = 2t_R(C_p)^2 = 15 \text{ accidental coincidences/s}$$

where:

$$t_R = 7 \cdot 10^{-9} \text{ s}$$

$$C_p = C_p^I + C_p^C$$

and

$$C_p^I = 2.5 \cdot 10^4 \text{ c/s}$$

$$C_p^C = 8.4 \cdot 10^3 \text{ c/s}$$

This accidental coincidence count rate can be estimated from measuring the singles count rate of the NE102 detector.

The net coincidence signal from fast fission will vary with the water concentration in the sandstone formation as shown in Figure 22.

The minimum detectable level (MDL) for uranium from the coincidence signal with 3 sigma (standard deviation) precision for a sandstone formation with 13 percent water content is calculated from equation (4) in Section 3 for $k = 3$ to be:

$$MDL = 3 B^{1/2} / R$$

where:

B = Background counts in a measurement time, t_m

R = Signal counts in a measurement time, t_m , per unit quantity (e.g., percent concentration) of the substance (e.g., uranium) causing the signal

substituting:

$$b = B/t_m = \text{background c/s}$$

$$r = R/t_m = \text{signal c/s per unit quantity}$$

gives:

$$(5) \quad \text{MDL} = 3 b^{1/2}/r t_m^{1/2}$$

From the above discussion:

$$b = Co_{acc} = 15 \text{ accidental coincidences/s}$$

$$r = 110 \text{ coincidences/s per percent of U}$$

and:

$$\text{MDL} = 3 (15)^{1/2}/110 t_m^{1/2} = 0.11/t_m^{1/2} \text{ percent of U}$$

For example, if the gross coincidence count rate is summed for 10 s, then the MDL is $0.11/10^{1/2} = 0.035$ percent of U

6.5.2 COINCIDENCE SIGNAL FROM SLOW-NEUTRON FISSION

The slow-fission coincidence signal can be separated from the fast-fission coincidence signal by anti-coincidence with the alpha pulses, C_a .

The slow-neutron fission of ^{235}U is assumed to produce 2.5 prompt neutrons with an average energy of 1 MeV and 8 prompt gamma rays with an average energy of 0.9 MeV. The slow-fission coincidence signal for a sandstone formation with 0.1 percent uranium and 13 percent water is calculated to be 37 coincidences/s (or 370 coincidences/s per percent of U).

The accidental coincidence rate is estimated to be:

$$Co_{acc} = 2t_R(C_p)^2 = 1 \text{ accidental coincidence/s}$$

where:

$$t_R = 7 \cdot 10^{-9} \text{ s}$$

$$C_p = C_p^I + C_p^c$$

and

$$C_p^c = 8.4 \cdot 10^3 \text{ c/s}$$

$$C_p^I = 0 \text{ (Eliminated by anti-coincidence)}$$

This accidental count rate can be estimated by measuring the singles count rate from the NE102 that is in anti-coincidence with C_a .

The minimum detectable level for uranium from this coincidence signal with 3 sigma precision for a sandstone formation with 13 percent water content is calculated from equation (5) to be:

$$MDL = 0.008/t_m^{1/2} \text{ percent of U}$$

If $t_m = 10 \text{ s}$ for scanning, the MDL for slow neutron fission coincidence becomes:

$$MDL = 0.008/10^{1/2} = 0.0025 \text{ percent of U}$$

After correction for the water content of the formation, the measured ratio of the fast-fission coincidence count rate to the slow-fission count rate should be a constant for a sandstone formation. Consequently, the presence of thorium in the formation should change this ratio because thorium only undergoes fast-neutron fission.

7. CORRECTION TECHNIQUES

Several techniques can be employed to correct the responses of the Borehole Neutron Diagnostic Probe.

The alpha particle count rate, C_a , is an accurate monitor of the output of the neutron generator and can be used to normalize the measured responses to a common neutron output.

A random accidentals spectrum can be used to correct the inelastic gamma ray spectral response, or the singles count rates could be used to calculate the fraction of the non-time correlated gamma ray spectrum needed for this correction.

The count rate from the NE102 can be used to calculate the accidental background for prompt gamma/prompt neutron coincidence response.

The presence of water in the borehole can be detected by the 0 to 10^{-9} s segment of the time dependent inelastic gamma ray signal and this information could be used to correct the other responses, if the correction factors were known. For example, the photopeaks in the inelastic and capture gamma ray spectra can be used to identify the formation. If it is a sandstone formation, then the 10^{-9} to 10^{-8} s segment of the time dependent inelastic gamma ray signal can be used to determine the percentage of water in the formation, and this information can be used to correct the spectral responses for the water concentration in a sandstone formation. Measurement of the water concentration and the variation of the fission coincidence signal versus water concentration, as illustrated in Figure 22, can be used to correct this response.

Figure 22   Variation of the Net Measured Fast Neutron Fission
 Coincidence Count Rate from a Sandstone Formation
 Containing 0.1% Uranium Versus Water Content

8. GEOPHYSICAL PARAMETERS

A number of geophysical parameters of interest to uranium exploration can be determined from the responses of the Borehole Neutron Diagnostic Probe. These are discussed in the following paragraphs.

8.1 URANIUM CONCENTRATION

The concentration of uranium can be estimated from the sum of the prompt gamma/prompt neutron coincidence count rates from fast-neutron and slow-neutron induced fission after correction for accidental coincidences.

8.2 FORMATION IDENTIFICATION

The sandstone formation can be identified from an analysis of the prominent high energy photopeaks in the inelastic-gamma ray spectrum and from the Si photopeaks in the capture gamma ray spectra.

8.3 CONCENTRATION OF WATER IN THE FORMATION

The concentration of water in the formation can be estimated from the hydrogen capture photopeak and/or from the time dependent inelastic-gamma ray response. (This variation has only been examined for sandstone, it may have a different variation for other formations or for sandstone formations with a different bulk density.)

8.4 POROSITY

To a first approximation, the porosity of the sandstone formation is defined by the equation:

$$\rho_B = \rho_s(1 - \Phi) + \Phi_w \rho_w$$

Rearranging:

$$(6) \quad \Phi = 1 - (1 - \Phi_w) \frac{\rho_w}{\rho_B} \frac{\rho_B}{\rho_s}$$

where:

ρ_B = bulk density of the formation

ρ_s = density of the sandstone

Φ = porosity of the sandstone (fractional volume)

Φ_w = fractional volume occupied by free water in the formation

ρ_w = density of water

If all of the water in the formation is assumed to be free water, then the concentration of free water in the formation,

$$C_w = \frac{\Phi_w \rho_w}{\rho_B}, \text{ can be estimated from the time dependence of the time}$$

correlated signal from the NE102 and/or from analysis of the capture gamma ray photopeak for hydrogen and the inelastic gamma-ray photopeaks for oxygen.

The concentration of the sandstone matrix in the formation,

$$C_s = \frac{\rho_s}{\rho_B}, \text{ is the sum of the concentrations of its constituents, or}$$

$$C_s = \frac{\rho_s}{\rho_B} = C_{Si} + C_O + C_{Ca} + \dots$$

$$\text{where: } C_{Si} = \frac{\rho_{Si}}{\rho_B} = \text{measured concentration of silicon from a silicon photopeak}$$

$$C_O = \frac{\rho_O}{\rho_B} = \text{measured concentration of oxygen (corrected for water) from an oxygen photopeak}$$

$$C_{Ca} = \frac{\rho_{Ca}}{\rho_B} = \text{measured concentration of calcium from a calcium photopeak}$$

Substituting the above in equation (6) yields:

$$\phi = 1 - (1 - C_w) \{C_{Si} + C_O + C_{Ca} + \dots\}^{-1}$$

The precision of the above estimate of the porosity can be improved by including the concentrations of other elements in the formation. However, the accuracy of the above approximation for the porosity cannot be improved by nuclear techniques that cannot distinguish between free water, absorbed water, and water of crystallization in the formation.

8.5 BULK DENSITY

The time dependent and non-time dependent responses are expected to be dependent upon the bulk density as well as the hydrogen concentration. However, these variations with bulk density have not been studied in detail because of time limitations.

If the density of sandstone, $\rho_s = 2.645 \text{ g/cm}^3$, and if the ratio by weight of silicon in sandstone, $R = \frac{\rho_{Si}}{\rho_s}$, is a known constant, then the bulk density can be estimated from an estimate of the silicon concentration $\frac{\rho_{Si}}{\rho_B}$, which is proportional to the magnitude of one of the silicon photopeaks, i.e.,

$$C_{Si} = \frac{\rho_{Si}}{\rho_B} = \text{silicon concentration}$$

Dividing by $R = \frac{\rho_{Si}}{\rho_s}$ gives:

$$\frac{C_{Si}}{R} = \frac{\rho_{Si}}{\rho_B} \cdot \frac{\rho_s}{\rho_{Si}} = \frac{\rho_s}{\rho_B}$$

$$\text{and: } \rho_B = \frac{\rho_s R}{C_{Si}} = \frac{2.645 R}{C_{Si}} = \text{bulk density}$$

where:

$\rho_s = 2.645 \text{ gm/cm}^3 = \text{sandstone density}$

$R = \text{known fraction by weight of silicon in sandstone}$

$C_{Si} = \text{measured silicon concentration}$

8.6 URANIUM INDICATORS

The presence of vanadium, potassium, and thorium are usually indicators of the presence of uranium. As indicated in Figures 14 and 18, the presence of potassium and vanadium can be detected by the gamma ray spectrometer. The presence of thorium is observed from the 2.6 MeV peak in the natural background, which is obscured by the inelastic and/or capture gamma ray spectra, but could be observed by turning the neutron generator off. Because thorium undergoes fast-neutron fission but not slow-neutron fission, the ratio of the fast fission coincidence to the slow fission coincidences could be used to detect thorium (and to correct the coincidence response for the presence of thorium).

8.7 THERMAL NEUTRON MASS ABSORPTION COEFFICIENT

The "die-away" time of the capture gamma ray events is inversely proportional to the thermal-neutron mass absorption coefficient. However, observation of the "die-away" time using the associated particle technique for timing will require a low neutron source strength, which is not believed to be an efficient mode of operation of the Borehole Neutron Diagnostic Probe.

8.8 OTHER ELEMENTS

The presence of C, O, Ca, Cl, Fe, Al, and other elements² and the ratios of their abundance are useful for identification of the lithology for uranium exploration. As shown in Figures 14, 15, and 18, small photopeaks for these elements can be observed if they are

present in the sandstone formation.

8.9 BOREHOLE PARAMETERS

A number of borehole parameters, such as the presence of water in the borehole (discussed in Section 6.3), borehole diameter at the probe location, location of casing joints, etc. are of interest in borehole logging. The initial rise of the time dependent inelastic gamma ray response contains data related to these parameters. These effects have not been studied in detail.

9. PROTOTYPE SYSTEM DESIGN

The results of the study have been used for a preliminary design of a prototype Neutron Diagnostic Probe. The probe geometry is illustrated in Figure 23. The associated electronic block diagram is presented in Figure 24. The preliminary prototype design is based on practices believed to be prevalent in the well-logging industry and upon components (except for the neutron generator) believed to be readily available.

NEUTRON GENERATOR

A 2.5 inch diameter sealed tube continuous neutron generator is shown in Figure 23, however, only a 3.5 inch diameter is commercially available, which would be a modification of a 3.5 inch pulsed sealed-tube unit. Sealed-tube neutron-generator engineers believe that a 2.5 inch diameter sealed-tube continuous neutron generator at 10^7 n/s output would be easier to design and build than a 2.5 inch diameter sealed-tube pulsed unit, however, they have not been requested to design any to date.

ALPHA DETECTOR

Two suppliers of solid state alpha detectors with a "small hole in a disc" geometry that will withstand the bakeout temperatures required during the final outgassing of a sealed tube neutron generator have been located. The energy resolution but not the timing properties of a solid state detector with a thin active volume begins to deteriorate after exposure to about 10^{12} n/cm². Very poor energy resolution can be tolerated. The calculated lifetime of the alpha detector is greater than 2,000 hours of logging time.

ANTI-COMPTON DETECTOR SCINTILLATORS

The design and construction of a detector assembly, consisting of a 3 x 45 cm NaI crystal and a 5 x 45 cm NE102 cylindrical

plastic scintillator with 1 cm thick walls with appropriate light pipes should be straightforward. The gamma ray energy resolution of the NaI crystal observed by summing the outputs of a photomultiplier at each end of the crystal is estimated to be better than 11 percent (FWHM for ^{137}Cs) based on manufacturer's experience.

PHOTOMULTIPLIER

Conventional photomultipliers have been specified for the scintillation detectors. However, the timing performance could be improved by using two multi-channel plate photomultipliers operated in summation at each end of each scintillator.

HIGH-VOLTAGE SUPPLIES, PREAMPLIFIERS, AMPLIFIERS

The high voltage power supplies, preamplifiers, and linear amplifiers for the detectors are commercially available circuits that can be mounted and packaged for use in a 2.5 inch diameter probe in the borehole environment.

COINCIDENT CIRCUITS AND GATES

The coincidence circuits and gates are adaptations of available circuits that are redesigned, mounted, and packaged for use in a 2.5 inch diameter probe.

DOWNHOLE MULTICHANNEL ANALYZERS

The number of channels of data and the data rates are too large to drive conventional logging cables. Consequently, downhole conversion of analog signals to digital signals, prescaling, and spectral data storage are used to reduce the data flow rate. The inelastic gamma ray pulses are gated to an analog to digital converter (ADC) and the ADC output stored in a 1024 channel downhole multichannel analyzer (MCA) in the add mode.

Figure 23 Borehole Neutron Diagnostic Probe and Borehole

Figure 24 Block Diagram of Borehole Neutron Diagnostic Probe Electronics

The time dependent response of the inelastic gamma ray signal is measured by a time to amplitude convertor (TAC) and stored in a 50 channel MCA. The fission coincidence outputs are stored in two 10^4 count capacity scalers. The singles rates of the alpha detector and the NE102 detector are measured by prescalers and the prescaler output stored in scalers. The MCAs and scalers are cycled once per second and their outputs are sequentially multiplexed into one twisted pair of a conventional logging cable.

This type of circuitry is readily designed and packaged for downhole well-logging purposes, however, equivalent electronics for nuclear pulses is not commercially available.

SURFACE DATA ACQUISITION

The sequential outputs of the downhole scalers and MCAs are de-multiplexed and could be either:

1. stored in conventional scalers and MCAs;
2. printed out;
3. plotted on strip chart recorders; or
4. fed to a minicomputer.

DOWNHOLE POWER AND CONTROL

One twisted pair is used to supply power to the neutron generator. One twisted pair is used to supply power to the downhole electronics. A four-conductor cable (4HO) will be sufficient for this application if common grounds are used.

10. SUMMARY

The following signals from the proposed Borehole Neutron Diagnostic Probe, which uses the associated particle technique¹ for timing and spatial resolution of the events produced by 14 MeV neutrons, in a 4.5 inch borehole in a sandstone formation have been investigated:

- (1) The inelastic gamma-ray spectrum measured by a gamma ray spectrometer whose signal input is correlated with the time emission of a 14 MeV neutron into the formation.
- (2) The capture gamma-ray spectrum measured by a gamma ray spectrometer whose signal input is not correlated with neutron emission and has the time correlated events gated out.
- (3) The time dependence of the inelastic gamma-ray signal.
- (4) The time dependence of the capture gamma-ray signal.
- (5) The measured coincidence signal from the detection of prompt gamma rays and prompt neutrons from fission.

The variations of the estimated intensities of the above signals and associated backgrounds were used to select the desired angles ($5^\circ < \theta < 60^\circ$) of associated particle detection. These variations were then used to select a detector length, 45 cm, and detector location, 32.5 cm from the neutron source, that would be capable of detecting these signals. Several possible detector types and configurations were investigated for a 2.5 inch diameter probe and a single anti-Compton gamma ray spectrometer composed of a 3 cm diameter NaI crystal inside of a 1 cm thick NE102 cylinder was chosen as a compromise between feasibility, cost, and detection capabilities. A source strength of 10^7 n/s was chosen as a compromise between signal strength and reducing accidental coincidences.

The electronics needed to correlate and measure the desired signals were identified from readily available commercial

electronics, however these circuits will require repackaging and redesigning for use in a 2.5 inch diameter probe.

A practical technique of measuring the time dependence of the capture gamma-ray signal without reducing the detection capability to the other signals was not conceived. The measured signals and associated backgrounds were estimated for the other signals for the chosen detector geometry.

The capture gamma ray signal is very sensitive to the silicon in the sandstone formation, and other elements² such as hydrogen, chlorine, and vanadium can be measured if the time available for measurement is increased. The inelastic gamma ray signal is sensitive to oxygen, carbon, silicon, calcium, chlorine, and other elements² in the sandstone formation, however measurement times of 100 s or longer and spectrum stripping techniques are required for precise measurements. The time dependent inelastic gamma ray signal is sensitive to the presence of water in the borehole and in the formation and should be useful for correcting the data for the presence of water and for estimating the porosity of the formation. The coincidence signal may be divided into coincidences from fast-neutron fission from ^{238}U or ^{232}Th and slow-neutron fission from ^{235}U . The ratio of these coincidence rates could be used to determine the concentrations of U and Th.

Two modes of operation are desirable with this system. The first mode is the scanning mode normally used for borehole logging, in which the probe is raised at a constant velocity and the signals are measured as a function of depth. The intent of the scanning mode is to determine the lithology. The second mode of operation is to position the probe in the center of a desired formation and to conduct precise measurements of the desired signals.

For example, the signals estimated for the proposed probe show that a sandstone formation can be rapidly located by measuring the count rate of a prominent silicon photopeak in the capture gamma ray spectrum. The probe can then be positioned at the depth of the sandstone formation and measurements made of the other elements and of the presence of water in the borehole and/or in the formation. The spectral data could be measured for a long time, e.g., 1,000 s,

and conventional stripping techniques used to determine the intensities of the inelastic and capture gamma ray photopeaks. This data could be corrected for the presence of water as estimated from the time dependent inelastic gamma ray signal, and then used to estimate the concentrations of the elements. In addition the porosity and bulk density of the sandstone formation could be estimated from the magnitudes of appropriate inelastic and capture gamma ray photopeaks.

The calculated minimum detectable levels (MDL) of several elements of interest are listed in Table 2. The MDL varies inversely with the square root of the time, t_m , available to make a measurement. For example, if $t_m = 10s$ in the scanning mode, then the MDL is decreased a factor of $10^{1/2}$ from the MDL for $t_m = 1s$.

The result of this effort has been the conceptual design of a borehole probe addressed to the simultaneous measurement of the following signals induced in the formation by a source of 14 MeV neutrons:

1. the inelastic-gamma ray spectrum,
2. the capture gamma ray spectrum,
3. the time dependence of inelastic-gamma radiation,
4. fast neutron fissions, and
5. slow-neutron fissions.

This conceptual design could be modified to improve the response to these measurements, e.g., by employing two anti-Compton spectrometers, but this would increase the potential production costs. Consequently, this conceptual design is expected to lead to a cost-effective borehole probe, whose primary virtues will be:

1. its versatility for simultaneously measuring several types of neutron induced radiations with a detection capability for each that is comparable to that of other probes that are dedicated to only one measurement in the scanning mode and
2. its capability to perform as an in situ analytical tool for determining the constituents of a formation more accurately than can be accomplished with several probes, each dedicated to one type of measurement.

TABLE 2

EXPECTED MINIMUM DETECTABLE LEVELS FOR ELEMENTS OF INTEREST

ELE- MENTS	RADIATION DETECTED	MDL/ $t_m^{1/2}$	MDL($t_m=10s$)	MDL($t_m=10^3s$)
H	2.23 MeV * Capture photopeak	$16/t_m^{1/2} \%H$	5%H	0.5 %H
C	4.44 MeV * Inelastic photopeak	$2.2/t_m^{1/2} \%C$	0.7%C	0.07%C
Si	3.54 MeV Capture Photopeak	$14/t_m^{1/2} \%Si$	4.4%Si	0.4 %Si
O	6.1 MeV * Inelastic photopeak	$18/t_m^{1/2} \%O$	5.7%O	0.57 %O
Cl	3.1 MeV * Capture photopeak	$6.2/t_m^{1/2} \%Cl$	2 %Cl	0.2 %Cl
Ca	3.6 MeV * Inelastic photopeak	$8.8/t_m^{1/2} Ca$	2.8 %Ca	0.28 %Ca
V	7.2 MeV * Capture photopeak	$3.18/t_m^{1/2} \%V$	1 %V	0.1 %V
^{235}U	Prompt gamma/ neutron co- incidence slow-neutron fission	$0.008/t_m^{1/2} \%U$	0.0025 %U	0.00025 %U
^{238}U	Prompt gamma/ neutron coin- cidence fast- neutron fission	$0.11/t_m^{1/2} \%U$	0.035 %U	0.004 %U

* Requires spectrum stripping analysis.

11. REFERENCES

1. Fast Neutron Physics, Part I; Marion, J.B., and Fowler, J.L, Interscience, Section IV.A.
2. Brafman, M., et al, Nuclear Techniques and Mineral Resources, 1977, IAEA, Vienna, 1977, p. 43-72.
3. Nuclear Ins. & Methods, Vol 63, p. 205-209, 1968. A. K. Furr et al.

APPENDIX A

A.1 TIME-DEPENDENT NEUTRON TRANSPORT

In this problem, the neutron source is considered to be a monoenergetic, isotropic point source imbedded in an infinite, homogeneous medium perturbed by the borehole and its contents. The formation can be assumed infinite, if its dimensions are large compared to the slowing down length of the source neutrons, and homogeneous, if the inhomogeneities in the formation can be averaged out over a volume element whose dimensions are small compared to the thermal neutron diffusion length. The perturbations introduced by the borehole will be treated later as a specific response case. Two categories of time-dependent neutron flux distributions are obtained for this problem. One is the fast neutron flux distribution, ϕ_f , the other is the thermal neutron flux distribution, ϕ_{th} .

A.2 FAST NEUTRON FLUX

A solution for the neutron flux distribution for this problem from the energy with which the neutrons are emitted from the source down to epithermal energies has been obtained from the literature^{1,2,3,4,5} as a function of position (r_1):

(I)

$$\phi = \frac{\lambda_s Q_n}{(4\pi)^{3/2} \tau L_f^3} \int_V e^{-(r_1^2/4L_f^2)} dV$$

where:

λ_s = Scattering mean free path

Q_n = Neutron source strength

ζ (Logarithmic Energy Loss) = $\text{Log}_n(E_n/E_{n+1})$

L_f = Slowing down length = $\{\lambda_{tr} \text{Log}_n(E_0/E_f)\}^{1/2}$

$\lambda_{tr} = \lambda_0^2/3\zeta\bar{a}_i$; $\bar{a}_i = (1-2/3A_i)$

A_i = Atomic weight of i^{th} element

From equation (I) and the references^{1,2,3} the energy dependent neutron flux distribution for a neutron energy (E) becomes:

(II)

$$\phi(E) = \phi_1 \int_{\Omega} \int_{t_1}^{t_2} \frac{(2E/m)^{3/2} t^2}{(\text{Log}_n(E_0/E_f))} e^{-(2E/m)t^2/4\lambda_{tr} \text{Log}_n(E_0/E_f)} d\Omega dt$$

where:

$$\phi_1 = \frac{\lambda_s Q_n}{(4\pi)^{3/2} \zeta \lambda_{tr}^{3/2}}$$

$$r = (2E/m)^{1/2} t$$

$$d^3r = r^2 dr d\Omega$$

$$d\Omega = \sin\theta d\theta d\phi$$

$$dr = (2E/m)^{1/2} dt$$

Also from equation (I) and references^{1,2,3}, the time dependent neutron flux is:

(III)

$$\phi(t) = \phi_1 \int_{\Omega} \int_{E_1}^{E_2} \frac{(2E/m)^{1/2} t^3}{m \text{Log}_n(E_0/E_f)} e^{-(2E/m)t^2/4\lambda_{tr} \text{Log}_n(E_0/E_f)} d\Omega dE$$

where: $dr = \frac{1}{m}(2E/m)^{-1/2} t dE$; for a constant time (t)

Because the variables r , E_n , and t are interdependent, the use of these solutions will result in separate but correlated solutions for the production rates of neutron-induced radiation and for the response equations. The choice will depend upon whether the variables (r), (E_n) or (t) are being examined.

A.3 THERMAL NEUTRON FLUX FOR FORMATIONS WITH LOW HYDROGEN CONTENT

The thermal neutron flux distribution for a medium with low hydrogen content^{1,3,4} is:

(IV)

$$\phi_{th} = \int_V \frac{Q_n V_{th}}{4\pi r D_{tr}} e^{-L_f^2/L_d^2} \left[e^{-r/L_d} (1 + \text{Erf}(r/2L_f - L_f/L_d)) + e^{+r/L_d} (1 - \text{Erf}(r/2L_f + L_f/L_d)) \right] dV$$

where Erf (x) is the error function which is defined as follows:

$$\text{Erf}(x) \equiv \frac{2}{\sqrt{\pi}} \int_0^x e^{-u^2} du$$

For Large r the solution has the form¹

(V)

$$\phi_{th} = \frac{Q_n V_{th}}{4\pi D_{tr}} e^{-L_f^2/L_d^2} \int_V \frac{e^{-r/L_d}}{r} dV$$

where:

L_f is the slowing down length

L_d is the diffusion length

D_{tr} is the transport diffusion coefficient

V_{th} is the thermal neutron velocity

substituting for L_f , L_d and D , where:

$$L_f^2 = \lambda_{tr} \text{Log}_n E_0/E_f$$

$$L_d^2 = \{\lambda_{tr}(\text{scattered}) \lambda_{tr}(\text{capture})\}/3$$

$$D = \lambda_{tr} V_{th}$$

yields:

(VI)

$$\phi(E) = \frac{Q_n E}{2\pi \lambda_{tr} m} e^{-L_f^2/L_d^2} \int_{\Omega} \int_{t_1}^{t_2} t e^{-(2E/m)^{1/2} t/L_d} d\Omega dt$$

From reference¹² the time dependent neutron flux for thermal neutrons in a medium of low hydrogen content is:

(VII)

$$\phi(t) = \frac{Q_n e^{-L_f^2/L_d^2} e^{-\Sigma_{tr} t}}{(4\pi) \lambda_{tr}} \int_{\Omega} \int_{E_1}^{E_2} \frac{e^{-(2E/m)^{1/2} t/L_d} t^2}{m(2E/m)^{1/2}} dE d\Omega$$

The value of $\phi(t)$ for a given t can only be calculated by numerical integration.

A.4 GENERAL RESPONSE EQUATIONS

The type of neutron-induced radiation and its variables depends upon the choice of the doubly-differentiated cross-section $d^2\sigma/d\Omega_1 dE_1$, the type of neutrons, i.e., fast or thermal neutrons, and the variables in the neutron flux distribution function.

For example, the total gamma ray response for a specific choice of neutron flux distribution, in terms of arbitrary variables "u" and "v", would be:

(VIII)

$$J_T(uv) = \sum_i J_i(u,v)_{n\gamma_c} + \sum_j J_j(u,v)_{nn'\gamma} + \dots$$

Using this general description we can define, time, space, and energy dependent responses by simply integrating the response functions with respect to all other variables except the one which we are interested in.

A.5 TIME DEPENDENT RESPONSES

The response to prompt gamma radiation induced by fast neutrons from 14 MeV to epithermal energies will be the sum of the responses to all of the fast neutron interactions that produce gamma rays, which to a first approximation is:

(IX)

$$J_{\text{fast}}(uv) = \sum_i \left[J_i(uv)_{nn'\gamma} + J_i(uv)_{n\gamma_c} \right]$$

Equation (IX) represents the inelastic scattering and fast neutron capture mechanisms, which consistently have the highest cross-sections for the elements in which we are interested, e.g., Si, O, C, Ca, ..., ^{238}U . We can also breakup each of the J_i response functions into its components such that:

(X)

$$J_i(nn'\gamma) = P_1 \cdot N_2 \cdot P_2 \cdot P_3$$

where:

P = the neutron flux at the target area at a given solid angle

$$N_2 P_2 = \int_{\Omega_2} \int_{E_2} N_2 \frac{d^2\gamma}{d\Omega_2 dE_2} d\Omega_2 dE_2 \equiv \Sigma_2 = \text{Macroscopic cross-section of the target element}$$

P_3 = Gamma flux incident on the gamma detector from the target center at a given solid angle

Using equations (III), (IX) and (X), we can now define time dependent response due to fast neutrons as:

(XI)

$$J_{\text{fast}}(T) = \sum_i (\phi_2)_i \int_{\Omega} \int_{E_1}^{E_2} \int_{V_2} \frac{(2E/m)^{1/2} t^3}{m \text{Log}_n(E_0/E_f)} e^{-(2E/m)t^2/4L_f^2} e^{-\mu_1 r_2} d\Omega_1 dE_1 dV_2$$

where:

$$\phi_2 = \frac{Q_n \lambda_s}{(4\pi)^{3/2} \zeta \lambda_{tr}^{3/2}} (\Sigma_{nn'\gamma} + \Sigma_{n\gamma} + \dots)$$

In the thermal region, the prompt gamma ray production is expected to be primarily from thermal neutron captures. Using equations (VII), (IX), and (X), the time-dependent response of the gamma radiation from thermal neutron capture in formations with low hydrogen content is:

(XII)

$$J_{\text{th}}(T) = \sum_i \phi_3 \int_{V_2} \int_{\Omega} \int_{E_1}^{E_2} \frac{e^{-(2E/m)^{1/2} t/L_d}}{m(2E/m)^{1/2}} e^{-\mu_1 r_2} d\Omega_1 dE_1 dV_2$$

where:

$$\phi_3 = \frac{Q_n e^{-L_f^2/L_d^2}}{(4\pi) \lambda_{tr}} (\Sigma_{n\gamma})_i e^{-(\Sigma_{tr})_i t}$$

A.6 SPECTRAL RESPONSES

From the discussions in Section A.2 and A.6 and equations (II), (IX) and (X), the spectral response for inelastic-gamma radiation for fast neutrons is:

(XIII)

$$J_{\text{fast}}(E) = \sum_i (\phi_4)_i \int_{V_2} \int_{\Omega} \int_{t_1}^{t_2} \frac{(2E/m)^{3/2} t^2}{\text{Log}_n(E_0/E_f)} e^{-(2E/m)t^2/4L_f^2} e^{-\mu_1 r_2} d\Omega_1 dt_1 dV_2$$

where:

$$\phi_4 = \frac{\lambda_s Q_n}{(4\pi)^{3/2} \zeta \lambda_{tr}^{3/2}} (\Sigma_{nn'\gamma})$$

Similarly, the spectral response for capture-gamma radiation for thermal neutrons for a medium of low hydrogen content from equations (VI), (IX) and (X) is:

(XIV)

$$J_{\text{th}}(E) = \sum_i (\phi_5)_i \int_{V_2} \int_{\Omega} \int_{t_1}^{t_2} (2E/m)t e^{-(2E/m)^{1/2} t/L_d} e^{-\mu_1 r_2} d\Omega_1 dt_1 dV_2$$

where:

$$\phi_5 = \frac{Q_n}{4\pi \lambda_{tr}} e^{-L_f^2/L_d^2} (\Sigma_{n\gamma})$$

A.7 FISSION PROMPT-GAMMA/PROMPT-NEUTRON COINCIDENCES

Equation (XIII) in Section A.6 is the spectral response for inelastic gamma radiation, but if $(\Sigma_{nn'\gamma})_i$ is interchanged with $(\Sigma_{\text{fiss}}(E))_i$ which includes the number of prompt gamma rays per fission of i^{th} element $n_f(E_n)$ as a function of incident neutron energy, the equation becomes the spectral response for prompt

fission gamma rays. However, in a fission reaction, prompt neutrons are emitted simultaneously with prompt gamma rays.

Therefore, the fission cross-section is multiplied by the number of prompt neutrons per fission and by the number of prompt gamma rays per fission to define a coincidence cross-section, which is:

(XVI)

$$J_{\text{fast}}(E_{\gamma_p/n_p}) = \sum_i (\phi_6)_i \int_{V_2} \int_{\Omega_1} \int_{t_1}^{t_2} \frac{(2E/m)^{3/2} t^2}{(\text{Log}_n(E_0/E_f))} e^{-(2E/m)t^2/4L_f^2} e^{-\mu_1 r_2} d\Omega_1 dt_1 dV_2$$

where:

$$\phi_6 = \frac{Q_n \lambda_s}{(4\pi)^{3/2} \zeta \lambda_{tr}^{3/2}} (\Sigma_{\text{fiss.}}) (E_{\gamma_p/n_p})$$

The modifications outlined above could also be applied to equation (XIV) in Section A.6 for the thermal neutron spectral response to obtain the fission (γ_p/n_p) prompt-gamma/prompt-neutron coincidence response for thermal fission, which may be of future interest.

A.8 THE RELATION BETWEEN SPECTRAL RESPONSES AND ACTUAL COUNTS PER SEC PER MeV

The $T(d,n) \text{He}^4$ reaction has a 17.6 MeV positive Q value, which provides the residual nucleus (He^4) with sufficient energy to be easily detected. If the alpha particles are detected at a known solid angle with respect to the incident beam, then the associated neutrons have a definite energy in a definite spatial direction, i.e., the solid angle in which the alpha particle flux is detected defines the conjugate solid angle of the neutron flux.

Using the foregoing argument, the initial neutron source flux can be related to the associated alpha flux, or:

$$\left(\frac{Q_n}{4\pi} d\Omega \right) \equiv \left(\frac{Q_\gamma}{4\pi} d\Omega \right)$$

The appropriate response functions, i.e., $J_i(u,v)$, are converted to counts per sec per MeV by multiplying the response functions with the appropriate detector efficiency, $s(E_\gamma)$ and integrating over the energy range of interest.

That is:

$$C_i(T) = \int_{E_1}^{E_2} J_i(T) s(E_\gamma) dE_\gamma$$

$$C_i(E) = \int_{E_1}^{E_2} J_i(E) s(E_\gamma) dE_\gamma$$

$$C_i(E_\gamma/E_n)_p = \int_{E_\gamma} \int_{E_n} J_i(E_\gamma/E_n)_p s(E_\gamma)_p s(E_n)_p dE_\gamma dE_n$$

etc.

A.9 APPLICATION TO A SANDSTONE FORMATION

The preceding theory may be applied to a sandstone formation by substituting the physical characteristics of a sandstone formation for the appropriate terms used in the equations in this Appendix. The neutron transport terms defined in this Appendix are summarized in Table 1. The neutron transport formulae that are used in this Appendix are also summarized in Table 2. The physical characteristics of the elements in a sandstone formation are tabulated in Table 3. The neutron transport characteristics of the elements in a sandstone formation are tabulated in Table 4. The calculated values of the neutron transport formulae for a sandstone formation with different water concentrations are listed in Table 5.

The values tabulated in these tables were used in the equations in this Appendix to produce the figures in the main text of this report.

TABLE 1

NEUTRON TRANSPORT TERMS^{1,2,3,7,8}

A_i = The atomic weight of the i^{th} element

W_i = The weight fraction of each i^{th} element

δ_{eff} = The effective density of the rock in gm/cm^3

δ_i = The density of the i^{th} element in the composition

M_i = Molecular/Atomic weight of the i^{th} element in the composition

V_i = Volume of the i^{th} element as a fraction in the composition

σ_s = Scattering cross-section

σ_c = Absorption/capture cross-section

N = Avogadro's number

n_i = Number of molecules of the i^{th} element in the composition

v_{th} = The velocity of thermal neutrons

TABLE 2

NEUTRON TRANSPORT FORMULAE ^{1,2,3,4,5,6,9,10,11}

Since diffusion theory deals only with the neutron density and neutron current, it cannot give the proper corrections for the anisotropic scattering in the laboratory system. From the rigorous solution of transport equations, it is possible to define transport corrections which will make the diffusion approximation terms more realistic.

The list of these corrected terms as they were used in the text is given below:

Effective Atomic Weight: $A_{\text{eff}} = \sum_i A_i W_i$

Effective Density: $\delta_{\text{eff}} = \sum_i \delta_i W_i$

Transport Mean Free Scattering Length: $(\lambda_{\text{tr}})_s = \left(\frac{1}{\sum_i n_i \sigma_{Si}} \right) \left(\frac{1}{1-2/3 A_{\text{eff}}} \right)$

Transport Mean Free Absorption Length: $(\lambda_{\text{tr}})_c = \left(\frac{1}{\sum_i n_i \sigma_{Ci}} \right) \left(\frac{1}{1-2/3 A_{\text{eff}}} \right)$

Transport Slowing Down Length: $(L_f)_{\text{tr}} = \frac{(\lambda_{\text{tr}})_s^2}{3\zeta(1-2/3 A_{\text{eff}})} \text{Log} \frac{E_0}{E}$

Transport Diffusion Length: $(L_d)_{\text{tr}} = \frac{\{(\lambda_{\text{tr}})_s (\lambda_{\text{tr}})_c\}^{1/2}}{3}$

Transport Diffusion Constant: $D_{\text{tr}} = \{(\lambda_{\text{tr}})_s v_{\text{th}}/3\}$

TABLE 3

PHYSICAL CHARACTERISTICS OF A SANDSTONE FORMATION

ELEMENTS	A_1 ($\mu\text{g/cc}$)	σ_{Si} (mb/str)	σ_{Si} (barns)	σ_{T} (barns)	$\sigma_{\text{Si}} \times 10^{-9}$ ($\text{cm}^2/\mu\text{g}$)	$\sigma_{\text{T}} \times 10^{-7}$ ($\text{cm}^2/\mu\text{g}$)	$A_1 \sigma_{\text{Si}}$ (cm^{-1})	$A_1 \sigma_{\text{T}}$ (cm^{-1})	λ_{Si} (cm)	λ_{T} (cm)	τ (constant)
Li	45	41.3	0.225	2.19	19.50	1.91	$8.77 \cdot 10^{-7}$	$8.60 \cdot 10^{-6}$	$0.114 \cdot 10^7$	$0.116 \cdot 10^6$	0.0268
B	82	5.4	0.029	1.60	1.64	0.89	$8.18 \cdot 10^{-8}$	$4.40 \cdot 10^{-6}$	$0.122 \cdot 10^8$	$0.225 \cdot 10^6$	0.1710
C	36600	19.5	0.106	1.65	5.32	0.83	$1.95 \cdot 10^{-4}$	$3.00 \cdot 10^{-3}$	$0.513 \cdot 10^4$	$0.330 \cdot 10^3$	0.1580
O	1370000	11.2	0.061	1.90	2.29	0.72	$3.14 \cdot 10^{-3}$	$98.60 \cdot 10^{-3}$	$0.318 \cdot 10^3$	$0.010 \cdot 10^3$	0.1200
Na	8750	60.0	0.326	2.30	8.55	0.60	$7.44 \cdot 10^{-6}$	$.53 \cdot 10^{-3}$	$0.134 \cdot 10^6$	$0.188 \cdot 10^4$	0.0840
Mg	18800	26.0	0.141	2.10	3.51	0.52	$6.59 \cdot 10^{-5}$	$.97 \cdot 10^{-3}$	$0.152 \cdot 10^5$	$0.102 \cdot 10^4$	0.0810
Al	67000	10.5	0.057	2.40	1.28	0.54	$8.54 \cdot 10^{-5}$	$3.58 \cdot 10^{-3}$	$0.117 \cdot 10^5$	$0.279 \cdot 10^3$	0.0720
Si	974000	17.6	0.096	3.20	2.05	0.69	$2.00 \cdot 10^{-3}$	$6.70 \cdot 10^{-2}$	$0.500 \cdot 10^3$	$0.149 \cdot 10^2$	0.0690
P	860	30.0	0.163	2.10	3.17	0.41	$2.73 \cdot 10^{-6}$	$3.72 \cdot 10^{-3}$	$0.365 \cdot 10^6$	$0.268 \cdot 10^4$	0.0630
S	7420	36.0	0.196	2.30	3.63	0.43	$2.73 \cdot 10^{-5}$	$.32 \cdot 10^{-3}$	$0.365 \cdot 10^5$	$0.312 \cdot 10^4$	0.0610
K	29200	80.0	0.435	3.10	6.70	0.48	$1.96 \cdot 10^{-4}$	$1.39 \cdot 10^{-3}$	$0.510 \cdot 10^4$	$0.719 \cdot 10^3$	0.0500
Ca	104500	15.1	0.082	3.50	1.24	0.53	$1.29 \cdot 10^{-4}$	$5.51 \cdot 10^{-3}$	$0.775 \cdot 10^4$	$0.181 \cdot 10^3$	0.0490
Ti	2650	18.1	0.098	2.60	1.24	0.33	$3.28 \cdot 10^{-6}$	$2.53 \cdot 10^{-6}$	$0.305 \cdot 10^7$	$0.116 \cdot 10^5$	0.0410
V	53	16.2	0.088	2.14	1.04	0.25	$5.22 \cdot 10^{-8}$	$1.34 \cdot 10^{-6}$	$0.192 \cdot 10^8$	$0.746 \cdot 10^6$	0.0380

TABLE 3 Continued

ELEMENTS	A_1 ($\mu\text{g/cc}$)	σ_{Si} (mb/str)	σ_{Si} (barns)	σ_{T} (barns)	$\text{In} \times 10^{-9}$ ($\text{cm}^2/\mu\text{g}$)	$\sigma_{\text{T}} \times 10^{-7}$ ($\text{cm}^2/\mu\text{g}$)	$A_1 \sigma_{\text{Si}}$ (cm^{-1})	$A_1 \sigma_{\text{T}}$ (cm^{-1})	λ_{Si} (cm)	λ_{T} (cm)	τ (constant)
Cr	100	52.1	0.283	2.18	3.28	0.25	$3.28 \cdot 10^{-7}$	$2.53 \cdot 10^{-6}$	$0.305 \cdot 10^7$	$0.395 \cdot 10^6$	0.0370
Fe	26200	65.5	0.356	3.50	3.85	0.38	$1.00 \cdot 10^{-4}$	$0.99 \cdot 10^3$	$0.100 \cdot 10^3$	$0.101 \cdot 10^4$	0.0350
Rb	724	13.3	0.075	2.30	0.53	0.16	$3.85 \cdot 10^{-7}$	$1.18 \cdot 10^{-5}$	$0.259 \cdot 10^7$	$0.847 \cdot 10^5$	0.0233
Ba	451	12.0	0.065	2.80	0.29	0.12	$1.29 \cdot 10^{-7}$	$5.55 \cdot 10^{-6}$	$0.775 \cdot 10^7$	$0.180 \cdot 10^6$	0.0143
U	18950	59.5	0.354	4.70	0.90	0.12	$0.17 \cdot 10^{-4}$	$2.27 \cdot 10^{-3}$	$0.112 \cdot 10^7$	$0.833 \cdot 10^5$	0.0084

See Table 1 in the Appendix for definition of symbols and references 12 to 56.

TABLE 4

NEUTRON TRANSPORT CHARACTERISTICS OF ELEMENTS IN A SANDSTONE FORMATION

ELE- MENTS	A_i ($\mu\text{g/cc}$)	σ_a (barns)	σ_s (barns)	σ_t (barns)	$\sigma_{ai} 10^{-7}$ ($\text{cm}^2/\mu\text{g}$)	$A_i \sigma_{ai} 10^{-3}$ (cm^{-1})	$A_i \sigma_{ti} 10^{-3}$ (cm^{-1})
Li	45	71.00	1.4	72.40	60.900	0.274	0.279
B	82	751.00	4.0	759.00	416.000	2.080	2.100
C	36600	0.00	4.8	4.80	0.002	0.008	9.600
O	1370000	0.00	4.2	4.20	0.000	0.010	22.500
Na	8750	0.53	4.0	4.53	0.128	0.112	9.660
Mg	18800	0.07	3.6	3.67	0.014	0.027	1.440
Al	67000	0.24	1.4	1.64	0.049	0.330	2.250
Si	974000	0.16	1.7	1.86	0.027	2.700	31.400
P	860	0.20	5.0	5.20	0.037	0.003	0.078
S	7420	0.52	1.1	1.62	0.090	0.068	0.212
K	29200	2.07	1.5	3.57	0.310	0.897	1.547
Ti	2650	5.80	4.0	9.80	0.730	0.192	0.324
V	53	5.00	5.0	10.00	0.550	0.003	0.006
Cr	100	3.10	3.0	6.10	0.340	0.003	0.007
Fe	26200	2.62	11.0	13.60	0.260	0.674	3.500
Rb	724	0.73	12.0	12.70	0.050	0.004	0.064
Ba	451	1.20	8.0	9.20	0.520	0.002	0.015
U	18950	7.68	8.3	16.00	0.090	0.017	0.035
Ca	104500	0.44	3.0	3.44	0.060	0.658	5.140

$$\Sigma_{th}^{ny} = 8.1 \times 10^{-3} \text{ cm}^{-1}$$

$$\Sigma_{th}^T = .293 \text{ cm}^{-1}$$

TABLE 5

NEUTRON TRANSPORT CHARACTERISTICS OF A SANDSTONE FORMATION

FORMATION	A_{Eff}	ξ	$\mu_{\text{Eff}} \text{ cm}^{-1}$	$\lambda_{\text{Tr}}^{nn'\gamma} \text{ cm}$	$\lambda_{\text{Tr}}^{t_f} \text{ cm}$	$\lambda_{\text{Tr}}^{n\gamma} \text{ cm}$	$\lambda_{\text{Tr}}^{t_{th}} \text{ cm}$	$L_f \text{ cm}$	$L_d \text{ cm}$
Sandstone	26.33	.0810	.116	173.5	5.59	127.1	3.50	16.10	12.17
Water	18.00	.0975	.028	--	45.90	90.5	0.79	119.10	4.87
Sandstone + 7% Water	27.56	.1490	.118	173.5	5.39	112.7	2.62	11.30	9.92
Sandstone + 13% Water	29.90	.2080	.120	173.5	5.35	104.9	2.18	9.50	8.73
Sandstone + 22% Water	33.86	.2960	.122	173.5	5.31	95.0	1.75	7.91	7.44

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A.10 REFERENCES FOR APPENDIX

1. Fermi, Enrico, 1967. Nuclear Physics. Chicago: University of Chicago Press. p. 181-200.
2. Glasstone, S. and Edlund, M.C., 1952. Elements of Reactor Theory. D. Van Nostrand, Inc. p. 38-61; 90-129; 137-150.
3. Segre, Emilio. 1965. Nuclei & Particles. Benjamin, Inc.
4. Radioactive Investigation of Oil & Gas Wells. 1965. Pergamon Press. p. 55-61; 177-213.
5. Soodak, H. 1962. Reactor Handbook, Vol. III. New York: Interscience, Inc. p. 5-9; 105-151.
6. Buccino, S.G. and Holladsworth, C.E. et al. 1964. Nuclear Physics. 60:17.
7. Reactor Physics Constants. 1963. Argon National Laboratory U.S.A. Atomic Energy Commission.
8. Marion, J.B. and Fowler, J.L. Fast Neutron Physics IV. New York; Interscience, Inc. p. 211-224.
9. Marion, J.B. and Young, F.C. 1968. Nuclear Reaction Analysis. New York: John-Wiley & Sons, Inc.
10. McCarthy, I.E. 1968. Introduction to Nuclear Theory. New York; John-Wiley & Sons, Inc.
11. Taylor, John R. 1972. Scattering Theory. New York: John-Wiley & Sons, Inc.
12. Manley, J.H. and Haworth, L.J. et al. 1942. Physics Review. 61:152.
13. UCRL. Vol. 4980. 1957. A. Bratenahl, J.M. Peterson, and J.P. Stoening.
14. Physics Review, Vol. 110, p. 927, 1958. J.M. Peterson et al.
15. Physics Review, Vol. 109, p. 947, 1958. J.F. Vervier et al.
16. Physics Review, Vol. 109, p. 1268, 1958. J.P. Conner et al.
17. Physics Review, Vol. 110, p. 466, 1959. J.L. Weil et al.
18. Bult. American Physical Society, Vol. 3, p. 336, 1958. L. Cranberg et al.
19. Reactor Handbook, Second Edition. 1962.

20. ANL 5800. 1962. p. 556-582.
21. Physics Review, Vol. 61, p. 152, 1942. J.H. Manley et al.
22. Nuclear Science Engineering, Vol. 46, p. 53-60, 1971.
Marion L. Stelts et al.
23. Physics Review, Vol. 130, p. 1471, 1963. M.H. MacGregor et al.
24. Physics Review, Vol. 114, p. 1584, 1959. J.S. Levin et al.
25. Nuclear Science & Engineering, Vol. 42, p. 352-366, 1970.
V.J. Orphan et al.
26. Nuclear Science & Engineering, Vol. 50, p. 98-107, 1973.
J.K. Dickens.
27. Nuclear Science & Engineering, Vol. 55, p. 168-187, 1974.
J. Lachkar et al.
28. Nuclear Science & Engineering, Vol. 50, p. 311-336, 1973.
J.K. Dickens et al.
29. Nuclear Science & Engineering, Vol. 40, p. 294-305, 1970.
Darrel M. Drake et al.
30. Nuclear Science & Engineering, Vol. 50, p. 243-247, 1973.
S.H. Hayes et al.
31. Nuclear Science & Engineering, Vol. 55, p. 17-23, 1974.
F. Rigaud et al.
32. Nuclear Science & Engineering, Vol. 42, p. 335-351, 1970.
R.E. Maerker et al.
33. Nuclear Science & Engineering, Vol. 35, p. 376-383, 1969.
G.I. Coulbourn et al.
34. Nuclear Science & Engineering, Vol. 35, p. 70-79, 1969.
Shawky F. Nassar et al.
35. Nuclear Science & Engineering, Vol. 62, p. 262-269, 1977.
William H. Miller et al.
36. Nuclear Data Sheets, Vol. 1, 2, 3, 4, 1959-1965.
Academic Press, New York.
37. AEC Research & Development Report. IDO-16408. Gamma-Ray Spectrum Catalog.
38. Nuclear Ins. & Methods, Vol. 63, p. 205-209, 1968.
A.K. Furr et al.

39. Nuclear Ins. & Methods, Vol. 63, p. 269-273, 1968.
J. Turkstra et al.
40. Nuclear Ins. & Methods, Vol. 121, p. 445-447, 1974.
R.A.J. Riddle et al.
41. Nuclear Ins. & Methods, Vol. 103, p. 585-588, 1973.
E.M. Diener et al.
42. Nuclear Ins. & Methods, Vol. 122, p. 443-446, 1974.
H.F. Steuer et al.
43. Nuclear Science & Engineering, Vol. 51, p. 119-123, 1973.
S. Wynehank et al.
44. Nuclear Science & Engineering, Vol. 40, p. 38-50, 1970.
N. Karayianis et al.
45. Nuclear Science & Engineering, Vol. 34, p. 313-327, 1968.
Harvey J. Amster.
46. Nuclear Inst. & Methods, Vol. 109, p. 349-353, 1973.
Horoshi Gotoh et al.
47. Nuclear Inst. & Methods, Vol. 124, p. 23-28, 1975.
D. Evers et al.
48. Nuclear Inst. & Methods, Vol. 63, p. 1-12, 1968.
M. Suffert et al.
49. Nuclear Inst. & Methods, Vol. 109, p. 301-304, 1973.
R. Igersheim et al.
50. Nuclear Inst. & Methods, Vol. 103, p. 479-491, 1973.
G.I. Crawford et al.
51. Soviet Physics-JETP, USSR, Vol. 28, p. 369-370, 1955.
V.V. Chavchanidze et al.
52. Nuclear Science & Engineering, Vol. 3, p. 186-200, 1958.
Eugene L. Wachspress.
53. Nuclear Science & Engineering, Vol. 2, p. 227-245, 1957.
E. Richard Cohen.
54. Nuclear Inst. & Methods, Vol. 37, p. 240-248, 1965.
G.G. Ohlsen.
55. Nuclear Science & Engineering, Vol. 2, p. 687-693, 1957.
H.D. Brown.
56. Small Accelerators for Teaching and Research, Vol. 1,
p. 250-253. P.A. Treads et al. 1967.