NEUTRON SOURCES FOR PROMPT-GAMMA NEUTRON-ACTIVATION ANALYSIS

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ABSTRACT

This paper reviews the history, characteristics and availability of neutron sources that are most commonly used in prompt-gamma, neutron-activation analysis (PGNAA) with sufficient detail to allow evaluation of the benefits of a type of neutron source for a particular PGNAA application. PGNAA measures in near real-time the elemental composition of bulk materials at locations such as conveyor belts or slurry pipes by analyzing the spectra of gamma rays emitted from each element when atoms absorb neutrons. A PGNA analyzer may have an isotopic neutron source or a neutron generator.

1.0 Introduction

Neutron sources that are used in commercially available PGNAA systems are described herein, and technical details are provided to help clarify relative benefits of the different types of neutron sources.

The neutron is a subatomic hadron particle with the symbol n or n0, a mass slightly larger than that of a proton and no net electric charge. With the exception of hydrogen, nuclei of atoms consist of protons and neutrons, which are therefore collectively referred to as nucleons. The number of protons in a nucleus is the atomic number and defines the type of element the atom forms. The number of neutrons in a nucleus determines the isotope of that element. For example, the abundant carbon-12 isotope has 6 protons and 6 neutrons, while the very rare radioactive carbon-14 isotope has 6 protons and 8 neutrons.i

"A major use of neutrons is to excite delayed and prompt gamma rays from elements in materials. This forms the basis of neutron activation analysis (NAA) and prompt gamma neutron activation analysis (PGNAA). NAA is most often used to analyze small samples of materials in a nuclear reactor whilst PGNAA is most often used to analyze subterranean rocks around bore holes and industrial bulk materials on conveyor belts."ii "Because free neutrons are unstable, they can be obtained only from nuclear disintegrations, nuclear reactions, and high-energy reactions (such as in cosmic radiation showers or accelerator collisions). Free neutron beams are obtained from neutron sources by neutron transport."iii

A neutron source is a device that emits neutrons. Isotopic neutron sources include elements that spontaneously fission, such as Califonium-252, and intimate mixtures of an alpha-emitting element, such as Americium-241, and beryllium. Electronic neutron generators of two types are also currently available. Accelerator-based neutron generators induce fusion between beams of deuterium or tritium ions and metal hydride targets that contain these isotopes. Plasma focus neutron generators of the Farnsworth-Hirsch fusor type produce controlled nuclear fusion by creating a dense plasma within which ionized deuterium or tritium gas is heated to temperatures sufficient for causing fusion and emitting neutrons.[iv]

PGNAA research was initiated by the U.S. Bureau of Mines in West Virginia in the 1960s, was further developed in the 1970s, primarily through research grants from the Electric Power Research Institute (EPRI) and then first commercialized in the 1980s. This technique of analyzing material composition is based on the principle that when an atom of an element absorbs a neutron, it emits an energy spectrum of

gamma rays that is unique for that particular element. When a material absorbs neutrons, the elemental composition of that material can be determined by analyzing the gamma-ray spectra emitted from the material. PGNAA is now used extensively in industry for real-time analysis of the composition of bulk materials for quality control and process control for mining and production of materials such as fertilizer, nickel, steel, cement, coal and biomass. It is also used for optimizing fuel utilization at power plants.

The availability of compact neutron sources for instruments in rugged industrial environments was key to the development of PGNAA. Both isotopic and electronic neutron sources are described in this paper.

2.0 Isotopic Neutron Sources

The most commonly used isotopic neutron source is Californium-252 (Cf-252), which is produced by irradiating transuranic elements in a nuclear reactor, where neutrons are absorbed in the starting material and subsequent reaction products, transmuting the starting material into Cf-252.[v] Cf-252 spontaneously fissions and produces neutrons reliably, with a high neutron output. A 40-microgram (21.6-mili-Curie) source produces 0.96 x 108 neutrons per second. These sources are readily available and involve no specific difficulties for licensing. Cf-252 has a half-life of 2.645 years with average neutron energy of about 2.4 MeV with 96% of the neutrons with energies ranging from 0.1 eV to approximately 6 MeV and peak emission rate near 1 MeV. A typical physical size of Cf-252 sources for PGNAA is 9.5 mm in diameter by 32 mm in length.

Americium-beryllium (AmBe) neutron sources emit neutrons as a result of the low-Z element, beryllium, absorbing high-energy alpha particles from the americium (alpha-n reaction). AmBe sources are the most common industrial sources based on an alpha-n-reaction.. These sources are highly reliable, but the neutron output per activity is significantly lower than for Cf-252. Sixteen Curies of Am-241 mixed with Beryllium is needed to produce 0.35 x 108 neutrons per second. Sixteen Curies is the maximum AmBe source activity that can be used without its becoming a “quantity of concern” as described below. The half-life of Am-241 is approximately 432 years; therefore, a source may still be near full strength when an analyzer has come to the end of its useful life. AmBe sources are readily available. The average energy of neutrons produced by Am-Be is about 4.5 MeV, with energies ranging from below 1 MeV to more than 8 MeV. Approximately 23% of neutron emission is below 1Mev with a mean energy of 400Kev.[vi] The physical size of the AmBe sources is dependent on the source strength. The size of a 16 Curie source may be about 30 mm in diameter by 40 mm in length.

Apparently, the world supply of Am-241 comes from Russia. The eventual cost of disposal of an unwanted source could be high and should be considered at time of acquisition.

3.0 Radionuclide Quantities of Concern

Following the attack on the World Trade Centers on September 11, 2001, there has been heightened concern for terrorist acts, and attention has also turned to concern for dirty bombs where terrorists could add radioactive pollution to conventional explosives and make large areas uninhabitable for a long period of time. In 2005 the NRC promulgated new regulations for radionuclides in “Quantities of Concern” in harmony with guidelines of the International Atomic Energy Agency (IAEA).[vii]

These regulations identified quantities of radioactive materials that would be of concern. Any entity that is licensed to have in possession an amount of radioactive materials greater than the “Quantity of Concern” must implement increased controls. These controls include the requirements of fingerprinting and a Federal Bureau of Investigation (FBI) identification and criminal history records check for individuals that have or will have unescorted access to radioactive materials in “Quantities of Concern,” as well as other safeguards, including alarms, locks, and significantly increased record keeping. In general these increased controls could place significant burden on an industrial site.

Although both types of sources described here for PGNAA would be affected by these regulations, the "Quantity of Concern" for Cf-252 is 5.4 curies (about 10,000 micrograms) and would never be exceeded by any practical analyzer, which might have from 10 to 100 micrograms. However, for AmBe, the Quantity of Concern is 16 curies, which limits the allowable source strength in an analyzer to about 0.35 x 10^8 n/s. This can limit the achievable precision and accuracy of an analyzer.

4.0 Electronic Neutron Generators

All types of electronic neutron generators have some characteristics in common. Neutron generator tubes must have either a continuous vacuum pumping system and/or periodic internal parts replacement. The vacuum system requires continuous servicing and periodic maintenance. Periodic tube replacement is required to replace internal parts and/or the gas fill. The replacement frequency is a function of the total hours of use that depletes the deuterium and tritium and adds fusion products inside the tube. Reliability depends on a sophisticated high voltage supply, an ion generator, and a control system.

Electronic neutron sources are much larger than isotopic sources. The neutron head is typically about 140 mm in diameter and about 750 mm long with a large diameter cable assembly extending from the neutron head to the power supply and control electronics that typically fill a large electronic cabinet some distance from the neutron-generator head. The size of the electronics is due primarily to the space required to generate high Voltage of 80,000 to 160,000 Volts for the neutron head. The neutron emission rates are a function of the probability of reaction or cross section. All else being equal, the emission rate for deuterium-tritium (D-T) is about 10 times that for deuterium-deuterium (D-D) and should be about 4 times that for tritium-tritium (T-T).

A D-D Neutron Generator emits neutrons with energy of about 2.4 MeV. This neutron energy does not allow measurement of carbon nor oxygen. The neutron emission rate is related to the power dissipated in the neutron generator tube. In pulse mode D-D neutron generators typically produce from 1 x 10^7 to 1 x 10^9 neutrons per pulse. This correlates to approximately 1 x 10^5 up to 1 x 10^7 neutrons per second steady state, with power dissipation from 200 watts up to 10,000 watts in the neutron generator tube that must be continuously removed in the form of heat in order to achieve controlled continuous neutron emission.

A D-T Neutron Generator uses the D-T reaction to emit neutrons with energy of about 14.1 MeV. This high energy allows measurement of both carbon and oxygen. The neutron emission rate is related to the power dissipated in the neutron generator tube. In pulse mode D-T neutron generators typically produce from 1 x 10^7 up to 1 x 10^{12} neutrons per pulse. This correlates to approximately 1 x 10^5 up to 1 x 10^{10} neutrons per second steady state, with power dissipation from 200 watts up to 10,000 watts in the neutron generator tube that must be continuously removed in the form of heat in order to achieve controlled continuous neutron emission.

A T-T Neutron Generator emits neutrons with energies in the range from thermal to 9 MeV. T-T neutron generators have recently been advertised by several vendors and promise advantages of measuring carbon and oxygen but without the shielding penalty associated with neutron energies greater than 10 MeV. The neutron emission rate will be lower than for D-T but higher than for D-D.

5.0 Costs of Neutron Sources

It is difficult to make a general comparison of the cost of neutron sources because there are so many variables that may affect that cost. However, it may be instructive to make some general comparisons that may be of use as a guide. The cost of money must be used in the comparison to properly compare high initial cost with lower initial cost but continued refurbishment costs. When purchasing an analyzer, the initial cost of the neutron source may be bundled into the purchase price, however, it is wise to determine future refurbishing costs for evaluating the real neutron source costs.

For Cf-252, if the price of 40-micrograms of source were $45,000 U.S., an additional $22,500 would be

spent every 2.6 years to add 20-micrograms of source. In the USA a wipe test must be performed on Cf-252 sources every six months and other countries have similar requirements. A wipe test requires about two hours at the site and its cost is often bundled with an overall maintenance agreement that includes training and preventive maintenance functions.

For AmBe a 16-Curie source may cost $200,000 U.S. and during 40 years will decay only 9%. Wipe tests as described above are also required for AmBe sources. If the source is eventually retired from use, the disposal cost could be high if the original manufacturer does not allow its return. Maintenance costs may be included in a maintenance contract but must be included in any evaluation of source costs.

For an electronic neutron generator, a D-T neutron generator may cost $100,000 U.S. The price for a D-D or a T-T neutron generator would be comparable. However, D-D cannot measure carbon and oxygen and no PGNAA installations with D-D nor T-T units has been identified; and, therefore, only D-T neutron generators are included in this comparison. They must be sealed for successful operation in a rugged environment and because tritium is radioactive and cannot be allowed to leak from the tube. The neutron generator head must be replaced periodically because of depletion of the target material or replacement of the gas fill. Quoted life-times have been getting better and apparently may be as high as 10,000 operating hours. The tube then must be replaced and the cost of replacement may be on the order of $40,000 for solid target generators. If the generator is used continuously all of the time, replacement is on the order of just over a year; if only 40 hours a week, replacement could be about 5 years. For inertial electrostatic confinement devices the gas replacement frequency is expected to be about every five years. By the very nature of a neutron generator, a lot of heat is generated in conjunction with the emission of neutrons; therefore, the cooling system associated with the neutron generator head will need periodic maintenance. The high-Voltage generator (about 100,000 Volts) will need periodic maintenance along with the protection system electronics that are used to ensure that no one enters the restricted areas while the neutron generator is operating. Although, these costs associated with maintenance of a neutron generator could be substantial, they may vary from one installation to another because of differences in the actual hardware and in the actual service conditions and are not included in estimated costs for Figure 1.

The graph in Figure 1 shows a possible cost comparison for four types of sources over a twenty year period assuming a 5% cost of money.

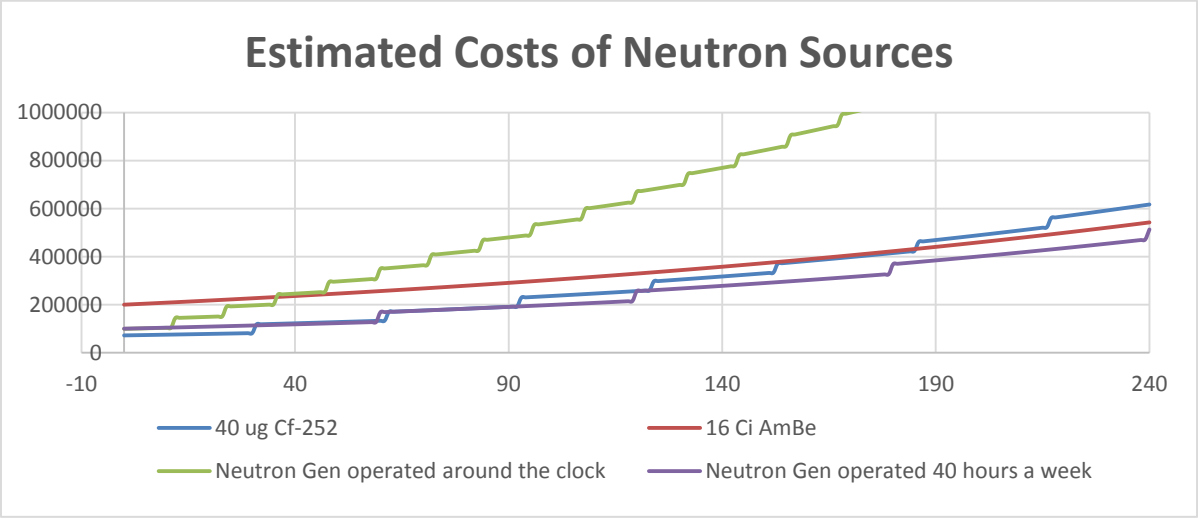

Figure 1 Relative Costs of Neutron Sources

6.0 Neutron Emission Spectra

Figure 2 and Figure 3 provide spectra and neutron emission rates for the four neutron source types discussed in this paper. The two figures are the same except for the vertical scale which has been expanded in Figure 3 to show the lower emission rates.

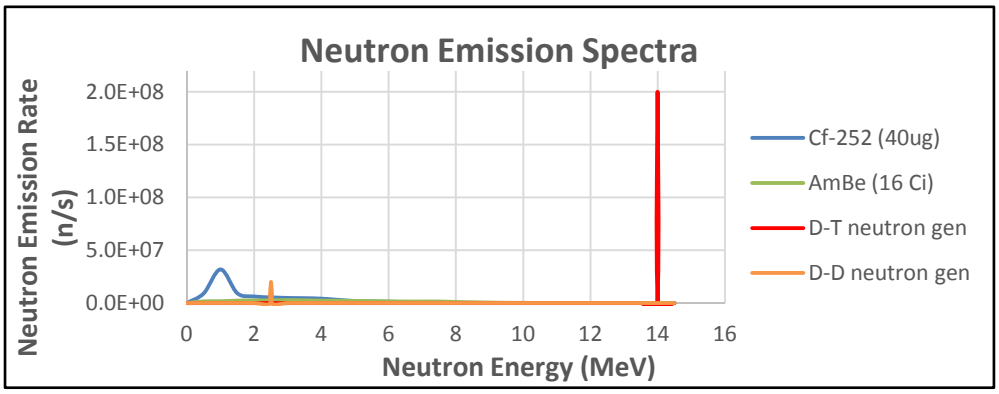

Figure 2. Neutron Emission Spectra

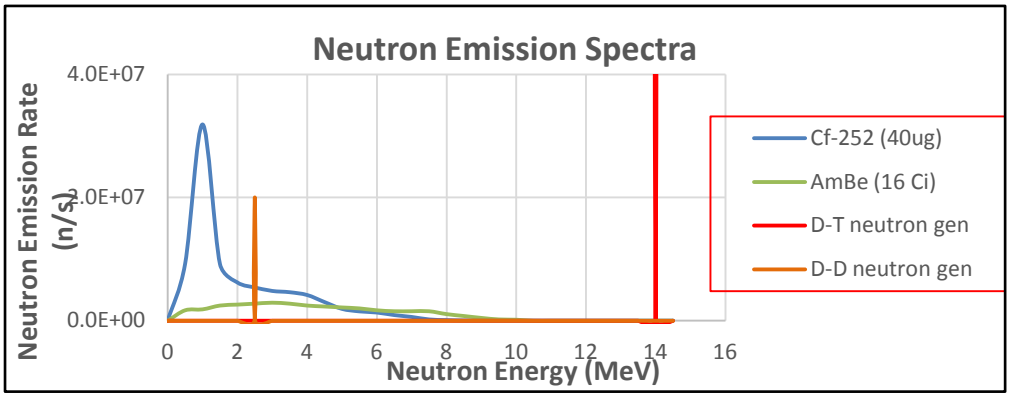

Figure 3 Neutron Emission Spectra (expanded scale)

There must be neutrons of energies greater than 5 MeV to be able to measure the inelastic spectrum of carbon and greater than 8 MeV to measure oxygen. These figures show that Cf-252, AmBe, and D-T neutron generators can measure carbon; AmBe and D-T neutron generators can measure oxygen. All other elements are excited by thermal neutrons (0.025 eV).

The very high neutron emission rates of D-T neutron generators is needed because there is significant absorption of neutrons in the moderating materials in order to reduce the neutron energy from 14,000,000

eV to 0.025 eV. Although the 14 MeV neutrons provide the benefit of enabling the measurement of carbon and oxygen, they also have the disadvantage of being more difficult to shield for personnel protection, both because of the high energy and because of the high neutron emission rate.

The AmBe spectrum has adequate high energy neutrons to measure both carbon and oxygen, but the emission rate is low and cannot easily be increased because of the Quantity of Concern that limits it to 16 Ci. Therefore the precision with which measurements can be made with AmBe is limited.

For D-D neutron generators, the emission rate is an order of magnitude lower than for a D-T neutron generator of the same construction and excitation because the probability of a D-D reaction taking place is an order of magnitude lower than for a D-T reaction. The elements carbon and oxygen cannot be measured using a D-D neutron generator. All neutrons emitted must be slowed down from 2.5 MeV to 0.025 eV in order to make the desired measurements, and, therefore, there is considerable loss of neutrons in the moderating materials. The cost of a D-D neutron generator is essentially the same as for a D-T neutron generator with several disadvantages and little advantage.

The Cf-252 isotopic neutron source emits a large abundance of neutrons at lower energies that can be moderated to thermal energy most efficiently, and, although it emits many lower-energy neutrons, it also has sufficient higher-energy neutrons to measure carbon. The cost of Cf-252 is lower than for the other neutron sources that could be considered for PGNAA. Its small size allows the use of multiple sources for obtaining geometrically uniform response from the material being measured.

7.0 Future Availability of Neutron Sources

Several vendors have **neutron generators** operating with PGNAA analyzers at customer sites. Future availability of these devices depends on the availability of deuterium and/or tritium as well as on market conditions.

Deuterium is available as heavy water in ordinary sea water at a concentration of about one part in 100,000 and is extracted for a variety of applications, including as the moderator for CANDU reactors. Tritium has a half-life of 12.3 years and decays into He-3 by beta decay. It is typically produced by irradiating lithium-6 with neutrons. Although the supply of government produced tritium has been somewhat restricted, it is readily available commercially and is used in self-illuminated signs.[viii]

Cf-252 was first isolated from a thermonuclear test in 1952. Useable amounts became available in 1967 from reactor irradiations, and U.S. Department of Energy (DOE) programs developed industrial and medical applications by loaning material to prospective users through their Cf-252 Market Evaluation Program.[ix] Now Cf-252 is widely used for research and for commercial, military, and safeguards applications. In May 2008 the DOE announced that it would no longer produce Cf-252, which caused a significant reaction among the many users. A consortium of users was set up to work with legislators and the government to ensure its long-term availability. Likewise, several government entities also identified the strategic importance of this element.

It became immediately apparent that Cf-252 had become an essential element in many applications in our society including national security. As a result, beginning 2009 the production facility at Oak Ridge National Laboratory (ORNL) was significantly upgraded to ensure long-term availability for its growing demand. Worldwide there are only two nuclear reactors capable of producing Cf-252: the High Flux Isotope Reactor (HFIR) at ORNL and the SMR3 (RIAR, Russia). ORNL supplies 70% of the world market demand. At a recent status meeting of the Californium-252 Consortium, the Department of Energy government representative stated: **"Cf-252 will be produced for the foreseeable future. HFIR to be operational beyond 2050"**[x]

Americium-241 for **AmBe** neutron sources is produced by separation from spent nuclear fuel where it has been transmuted from uranium to americium. It is widely used in commercial ionization chamber smoke

detectors, as well as, in neutron sources and industrial gages.[xi] However, the amount that can be used in a single PGNAA analyzer may be limited because of the "radionuclide quantities of concern" regulations from the IAEA and the NRC.

8.0 PGNAA Applications

Hundreds of PGNAA Analyzers using Cf-252 and some using other types of neutron sources have been sold around the world in a wide variety of applications that add value to operations. Coal mines can deliver more consistent quality to their customers while conserving valuable reserves. Coal burning power plants can monitor incoming fuel quality more effectively, can improve control of coal quality fed to the boiler, can have more confidence in complying with environmental requirements, and can aid in avoidance of costly fuel-related boiler shutdowns. These can contribute to a reduction in the cost of power to the customers. Cement Operations can better control the consistency of materials delivered from the quarry while reducing handling costs and conserving reserves and can improve the consistency of the raw mix for improving cement quality, reducing additive costs, extending kiln refractory life, and reducing energy consumption. Other Minerals, such as nickel, iron, bauxite, and fertilizers, achieve significant benefits by conserving energy and other costs and improving the quality of the product.

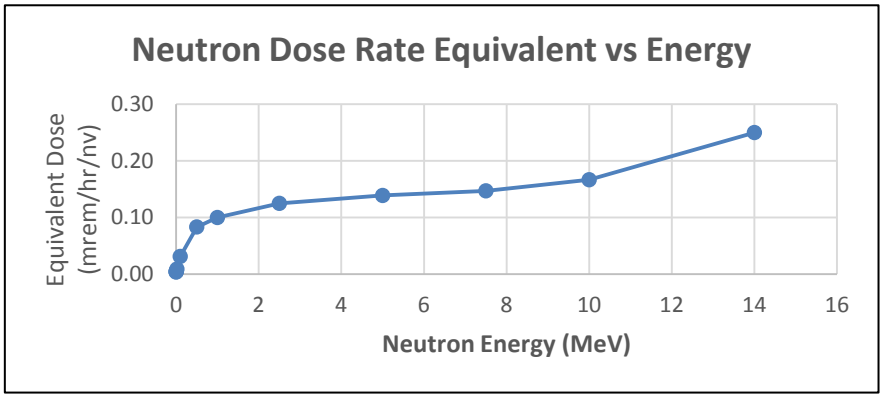

Figure 4. Equivalent Radiation Dose Rate vs Neutron Energy

9.0 Analyzer Shielding Considerations

Shielding in PGNAA analyzers 1) moderates (slows down) and focuses neutrons into the material that is being analyzed and 2) protects personnel from radiation. Shielding for personnel safety is described here, and Figure 4 shows that the damage in a human body from a single neutron increases as the neutron energy increases. Therefore, although higher energy neutrons are more difficult to shield, a higher percentage of them must be removed for personnel safety.

PGNA analyzers typically use hydrogenous materials such as polyethylene and paraffin for shielding. Low-atomic-weight elements moderate lower energy neutrons (below about 8 MeV) very efficiently. But higher-energy neutrons do not lose much energy nor change direction much when passing through low-Z materials, and, therefore, they penetrate shielding to a much greater depth. They do undergo inelastic interactions with nuclei and these interactions result in a cascade of lower energy particles including more lower-energy neutrons.[xii] Shielding studies for 14.1 MeV neutrons have shown that a combination of iron and polyethylene shielding is more efficient than either by itself. However, gamma rays from iron in a PGNAA analyzer would create an unacceptably high background at the energies of importance and would make elemental analysis difficult.[xiii] Shielding is much easier for the lower energy

neutrons from Cf-252 than for the higher energy 14 MeV neutrons of D-T neutron generators.

In summary, analyzers need more shielding with D-T neutron generators not only because higher energy neutrons are more destructive in tissue and more difficult to shield but also because the neutron emission rate from the source must be higher in order to have sufficient sensitivity for identifying elements that are excited by thermal neutrons. Analyzers with D-T neutron generators may use a fence around the vicinity of the analyzer to restrict access with an alarmed gate that must be closed while the analyzer is operating. Although the neutron generator can be turned off, that normally occurs outside of working hours when personnel are not around.

Table 1. Dose Equivalent vs Neutron Energies

Neutron Energy (MeV)	Flux ($n/cm^2/s$) for 2.5 mrem/hr	Dose (mrem/hr) per $n/cm^2/s$
Thermal	670	0.0037
0.0001	500	0.0050
0.005	570	0.0044
0.02	280	0.0089
0.1	80	0.0313
0.5	30	0.0833
1	24	0.1043
2.5	20	0.1250
5	18	0.1389
7.5	17	0.1471
10	17	0.1471
10 to 30	10	0.2500

Occupational Exposure Limits[xiv] are normally controlled by regulations of governmental agencies. In the U.S. holders of NRC licenses are limited by regulations published in Title 10 of the Code of Federal Regulations, Part 20 (10CFR20). An exposure rate of 2.5 mrem/hr is often used as a dividing point between those areas in which entry must be restricted from those to which workers may have free access. The radiation dose from neutrons is delivered in the form of secondary radiations produced by neutron interactions, and the dose equivalent from neutrons must take into account the different quality factors associated with the various secondary radiations. Table 1 "taken from 10CFR20, gives the neutron flux which will deliver a dose equivalent of 2.5 mrem/hour." [xv] A constant exposure of 2.5 mrem/hr for 40 hours per week for 50 weeks a year would give the maximum allowable dose for a radiation worker per the regulations.

Shielding calculations are complex and are done using computer programs such as MCNP that have been developed over many years for various aspects of nuclear science. However, simple shielding principles can allow understanding of the implications for different types of neutron sources for PGNAA. The distances from an unshielded source at which the dose rate would be 2.5 mrem/hr are i) 12.6 meters for a D-T generator (2×10^8 n/s), ii) 6.1 meters for a Cf-252 (0.96×10^8 n/s) source, and iii) 3.8 meters for an AmBe (0.35×10^8 n/s) source.

Calculating shielding thickness is much more complex than calculating distance from an unshielded source because the neutron cross sections of the materials in the shielding change with a change in neutron energy and the dose equivalent quality factor also changes with a change in neutron energy. Therefore, as a neutron is slowed down, its rate of interaction in the material is increased and the amount the neutrons contribute to radiation dose as they leave the shielding is also a function of the energy with which they escape. For fast neutrons the "macroscopic-effective-removal cross-section" is typically used with a Monte Carlo computer code to calculate shielding effectiveness.[xvi] Figure 5 shows that the $1/10^{th}$ thickness for borated polyethylene would be about 7.5 inches for 14 MeV neutrons but only about 3.5 inches for 2.5 MeV neutrons.[xvii] This means that the higher energy neutrons travel more than twice as far before 90% of them are scattered to a lower energy or absorbed. The scattered neutrons still have

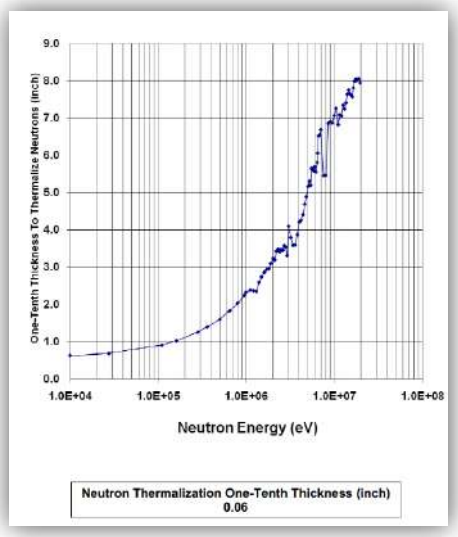

Figure 5. Neutron One-Tenth Thickness for Borated Polyethylene

high energy until they have scattered several times so that the amount of shielding that must be provided is much, much greater.

10.0 Coal Heat Value Measurements

Coal analysis laboratories determine the heat value of coal by burning a measured quantity of the coal and measuring the heat released in that process, typically in a bomb calorimeter. One of the significant applications of PGNAA for coal is the real-time measurement of the calorific value of the coal. This is done by calculating calorific value from the measurement of coal composition. At a coal mine or preparation plant this real-time measurement can improve the cost effectiveness and reliability with which the coal producer is able to meet contractual specifications. At coal-fired power plants, this real-time measurement offers the opportunity of controlling uniform fuel feed to the boilers for improving cost effectiveness of power generation.

PGNAA analyzers often use a moisture, ash-dilution approach for calculating BTU that uses a moisture-ash-free (MAF) heat value for which an average MAF heat value measured by the local lab is used, and the measured values of moisture and ash are used with that MAF value to calculate calorific value in real time. Alternatively, much work has been done deriving formulas for calculating calorific value of coal from analysis of coal composition. These formulas typically use percentages of carbon, hydrogen, sulfur, oxygen, nitrogen, and ash in the coal. Mason and Gandhixiii in about 1980 at the Institute of Gas Technology in Chicago, IL, achieved their best results with a formula in which they replaced the terms for oxygen and nitrogen with a constant, leaving only terms for carbon, hydrogen, sulfur, and ash. All three types of neutron sources, Cf-252, AmBe, and D-T generator, allow this approach.

11.0 The Need for Multiple Sources in a Single Analyzer

An important feature of an analyzer for providing consistent accurate measurements is the ability of the analyzer to measure an element with the same sensitivity at every point throughout the geometric cross-section of the material being measured. Excellent uniformity can be achieved by being able to spread the neutron sources and the detectors in an optimum pattern across the width of the conveyor. Cf-252 and AmBe sources are small enough to be easily located in proper positions for geometric uniformity, and there is very little cost penalty for having the total amount of source split into more than one module. Neutron generators, however, are large and their size, cost and shielding requirements inhibit the use of more than one source in an analyzer. The problem of being limited to using only one source is somewhat mitigated by the difficulty of moderating the neutrons from 14 MeV to thermal energy and many interactions that take place in the process, which tends to spread the neutrons over a larger area.

12.0 Neutron Emission Stability

Any change in neutron emission rate could result in a measurement error in a PGNAA analyzer. A change in the emission rate of an isotopic source is controlled by nature, is completely predictable and can be compensated by algorithms in the analyzer that allow for natural source decay. The neutron flux level for a neutron generator is determined by the electronic control system, which must provide some secondary measurement of output levels in order to predict or determine the actual output neutron flux. There are many factors that may affect the neutron emission rate of an electronic neutron generator and the control system must compensate for all such effects. Although it may be very good, an electronically controlled neutron flux cannot be as stable as the neutron flux from an isotopic source.

13.0 Conclusion

This paper has compared three types of neutron sources that are offered in commercially available PGNAA analyzers, Cf-252 and AmBe isotopic neutron sources and electronic neutron generators.

Neutron generators are an amazing accomplishment of science and engineering. They are miniature fusion reactors that fuse isotopes of hydrogen to produce energy and neutrons. Those with solid targets accelerate heavy hydrogen atoms to such high speeds (energies) that they fuse with target atoms of heavy hydrogen. Plasma focus neutron generators are able to create a dense plasma within a very small space for causing fusion and emitting neutrons. There is great benefit for applications such as well logging for which there is no neutron radiation to deal with while inserting a tube down a hole until the power is turned on and then there is no concern for shielding because the earth provides natural shielding.

In PGNAA applications neutron generators provide the benefits of being able to measure oxygen directly and of being able to be turned off when not needed. However, the high energy (14 MeV) neutrons are difficult to shield and cause much more tissue damage in living beings. This results in bulkier, more costly shielding and often perimeter fences to keep personnel away from operating analyzers. The complexity of the tubes and control electronics naturally have failure modes and will need long-term maintenance and repairs. The difficulty of moderating 14 MeV neutrons to thermal, 0.025 eV, demands a high neutron emission rate, which adds to the requirement for much shielding.

AmBe neutron sources have the advantages of being able to measure oxygen directly and a long half-life that maintains its neutron emission level for the entire life of an analyzer. However, the long half-life is also a liability that limits the neutron emission rate and thus the analyzer precision due to "Quantity of Concern" issues, causes the cost to be high, and raises the question of cost of disposal when it is no longer needed.

Cf-252 neutron sources have many advantages that have made them the source of choice for most PGNAA analyzers. They emit neutrons of energies from near thermal to 6 MeV, which allows direct measurement of carbon but not oxygen; however, with most of the emitted neutrons at lower energies, they are easy to moderate and shield. Therefore, the gamma-ray signal per emitted neutron is highest of any type source and the shielding requirement to completely protect personnel is the lowest. The initial cost is lowest and the long-term costs probably remain the lowest, depending future economic events and any maintenance required for other types of sources.

When all characteristics of the three types of neutron sources are considered, it becomes apparent why Cf-252 has been and continues to be the neutron source of preference for most PGNAA applications. It is the lowest cost, is most easily shielded for personnel protection, causes the least concern with respect to terrorism, provides excellent output stability that is independent of service conditions, and is, perhaps, the most likely to continue to be commercially available for the long-term future.

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