by David L. Chichester and James D. Simpson

Compact Accelerator Neutron Generators

For industrial applications that require neutrons, users have three primary sources from which to choose: nuclear reactors, radioisotopes, and accelerator-based neutron sources. Nuclear reactors are clearly the largest and most prolific sources of neutrons. However, their size, complexity, and cost have limited their industrial applications for purposes other than electricity generation.

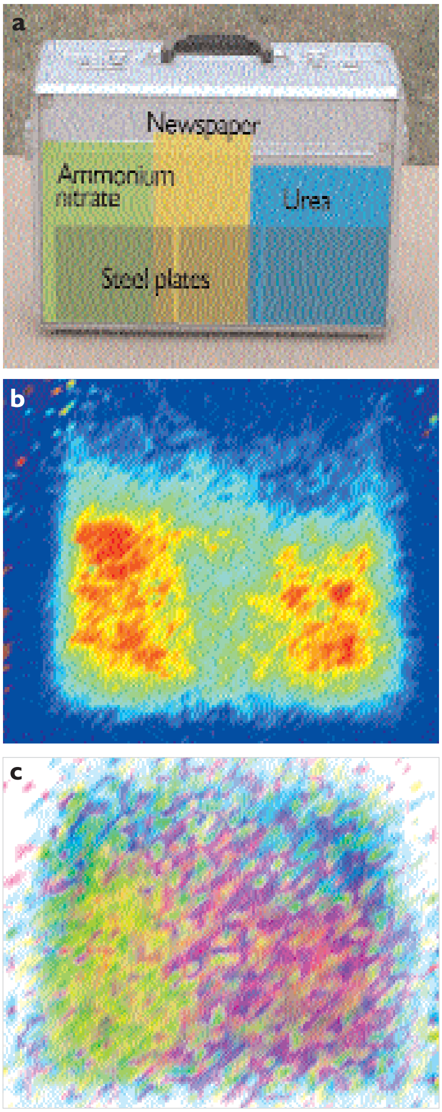
In contrast, radioisotope neutron sources are used in a myriad of industrial applications, including thickness gauging and petroleum exploration. Although radioisotope sources are ideal for fixed installations that run continuously, they are not well suited for applications that require pulsed neutrons, and they may create safety issues and logistical complications as well. Moreover, concerns have increased recently about the physical security of radioisotope sources because of their possible use in dirty bombs.

Particle accelerators are the third source of neutrons for industry. These systems vary in size and diversity, and they include large installations such as the Spallation Neutron Source under construction at Oak Ridge National Laboratory, and smaller photoneutron sources such as that at the Gaerttner Linear Accelerator Laboratory at Rensselaer Polytechnic Institute. Among the various light-ion accelerators, compact devices designed as hermetic, sealed tubes that use deuterium–deuterium (D–D) and deuterium–tritium (D–T) reactions have found the most widespread use in industry.

$$\mathrm{D} + {}^{2}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \mathrm{n} \qquad Q = 3.270\ \mathrm{MeV}$$
$$\mathrm{D} + {}^{3}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \mathrm{n} \qquad Q = 17.590\ \mathrm{MeV}$$

These accelerators generate neutrons of ~2.5 and ~14.1 MeV, respectively. Thousands of such small, relatively inexpensive systems have been built over the past five decades, and the number and variety of their applications are growing steadily (Figure 1).

The basic design of a modern compact accelerator neutron generator (Figure 2) does not vary much from those of other particle accelerators. It consists of a source to generate positively charged ions; one or more structures to accelerate the ions (usually up to ~110 kV); a metal hydride target loaded with either deuterium, tritium, or a mixture of the two; and a gas-control reservoir, also made of a metal hydride material. The most common ion source used in neutron generators is a cold-cathode, or Penning ion source, which is a derivative of the Penning trap used in Penning ion gauges. This simple ion source consists of a hollow cylindrical anode (usually biased 1–2 kV) with cathode plates at each end of the anode (usually at ground potential). An external magnet is arranged to generate a coaxial field of several hundred gauss within the ion source.



J. Kocher, Dynamics Technology Inc./P. Hurley and J. Tinsley, U.S. Dept. of Energy, Special Technology Laboratory

Figure 1. A case containing a newspaper, ammonium nitrate, steel plates, and urea (a) is examined with a pulsed neutron generator using associated particle imaging, which produces a two-dimensional density plot (b) and a yellow spectrum characteristic of ammonium nitrate (c).

When deuterium and/or tritium gas is introduced into the anode at a pressure of a few millitorr, the electric field between the anode and cathodes ionizes the gas. Electron confinement is established in this plasma because of the orientation of the electric and magnetic fields, which forces the electrons to oscillate back and forth between the cathode plates in helical trajectories. Although some low-energy electrons are lost and strike the anode, which creates more secondary electrons, most remain trapped and ionize more gas molecules to sustain the plasma. The ions are not similarly trapped, and when they strike the cathodes, they also release secondary electrons, which enter the plasma and help sustain it. Ions, however, can escape the chamber into the acceleration section of the tube through a hole at the center of one of the cathodes, called the exit cathode.

Other types of ion sources are also used in industrial applications, including hot-cathode sources, magnetrons, and radiofrequency ion sources. However, the simple design and durability of the Penning ion source have made it the most commonly used in industrial neutron generators.

Construction methods used in building sealed neutron tubes include joining techniques such as welding, metal brazing, ceramic-to-metal brazing, and glass-to-metal seals. Materials used in accelerator neutron systems include glass, ceramics, copper, iron, different alloys of stainless steel, and Kovar. Most compact accelerator neutron tubes are loaded with 1 to 2 Ci of tritium; for comparison, a typical tritium exit sign used in an airplane or hotel might contain as much as 10 to 20 Ci of the isotope.

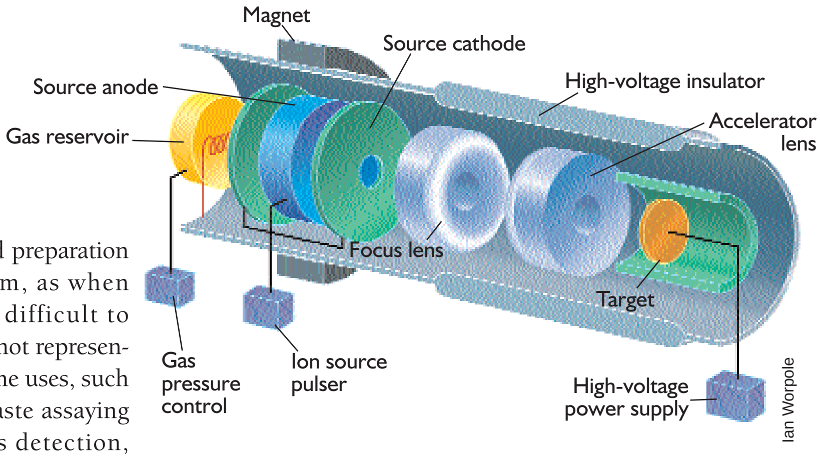


Figure 2. Schematic design of a sealed-tube neutron generator with a Penning ion source.

Ian Worpole

Industrial applications

Compact accelerator neutron generators are made by several companies (Table 2) and used for many industrial purposes (Table 1). Although the initial sealed-tube devices addressed the military's need for a long-lived neutron source, the technology made the transition to peaceful applications soon after World War II. The first commercial products were developed for petroleum exploration.

Since the development of these first systems, applications have focused on detecting and quantifying the presence of different elements in a variety of materials, with the goal of improving process optimization and control. Usually, neutron-generator-based systems can provide this information much more quickly than traditional laboratory techniques. Because fast neutrons have a large effective range of penetration in most materials—several tens of centimeters—neutron analysis of bulk materials has significant advantages over certain laboratory techniques. This is particularly true where sample collection and preparation are a problem, as when samples are difficult to obtain or are not representative. For some uses, such as nuclear-waste assaying or explosives detection, the noncontact, nondestructive, and remote-measurement capability that neutron analysis techniques allow are an additional advantage.

TABLE 1. APPLICATIONS OF NEUTRON GENERATORS

General area	Specific applications
Geophysical measurements	Mine mineral mapping and analysis Petroleum exploration Quarry mineral mapping and analysis Uranium exploration
Industrial process control	Cement process control Coal quality analysis Wall thickness analysis
Medical	Body composition measurement Diet and nutrition studies
Security	Explosives detection and identification Chemical weapon agent detection and identification Special nuclear materials detection and identification Land mine detection Unexploded ordnance inspection
General research	Fast neutron reference source for instrumentation Calibration source for neutrino observatory instrumentation Studies of electronic component susceptibility to radiation damage Multiphase flow analysis Nuclear reactor analysis Neutron radiography
Environmental	Nuclear waste assay Waste assay for Resource Conservation and Recovery Act Carbon sequestration quantification in soil

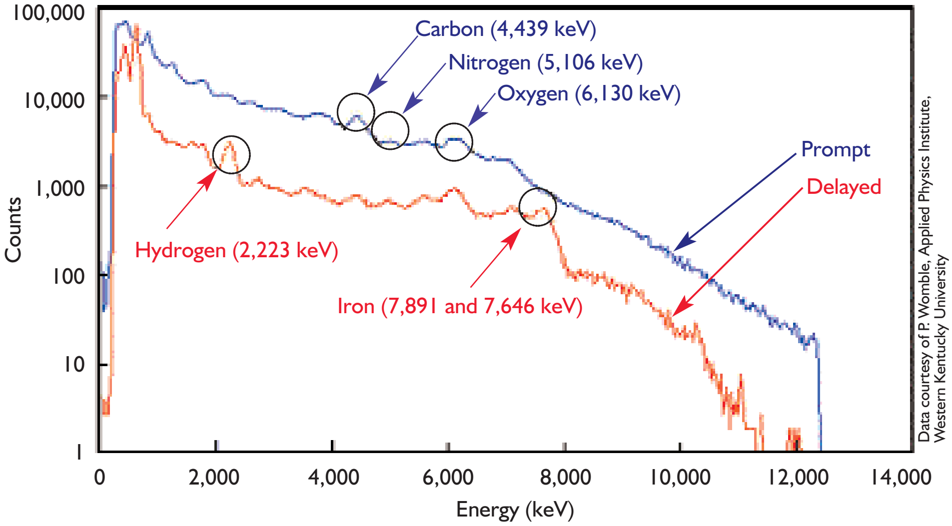
The most advanced industrial applications of compact accelerator neutron generators are in the petroleum industry, which has relied on the devices for nearly 50 years. These probes penetrate far more deeply into rock formations than most other techniques, and thus, they allow analysts to "see" farther than with other downhole probes. This capability is especially useful when analyzing cased holes, where neutron-based techniques allow the probe to measure rock properties behind steel casings.

Early probe systems used gas-filled thermal-neutron detectors to measure the thermal-neutron intensity decay over time between the neutron pulses emitted by the generator. Taking advantage of the large thermal-neutron absorption cross section of chlorine (33 barns for chlorine versus 0.33 barn for hydrogen) and subsequent improvements in the implementation of the technology, analysts began using measurements of thermal-neutron decay to distinguish between hydrocarbons and saline water in underground formations.

Tools for these measurements typically operate at 1,000 pulses/s, with each 100-μs pulse followed by a 900-μs pause before the next pulse. These respites allow enough time for the fast neutrons from each pulse to become fully thermalized and absorbed. Photon detectors are most commonly used in these tools; they measure gamma-ray intensity versus time, which is proportional in intensity to the number of surviving thermal neutrons.

Bulk-materials analysis

An important and growing market for neutron generators is in analyzing bulk materials. Taking advantage of recent improvements in neutron-generator performance that have extended typical operating lifetimes from a few hundred hours to several thousand hours, companies have built commercial systems for the real-time analysis of materials such as cement and coal moving on conveyor belts. Newer neutron-generator-based systems typically run both fast- and thermal-neutron activation analyses to measure the elemental content of the major constituents in the bulk material, and use stoi-



Data courtesy of P. Womble, Applied Physics Institute, Western Kentucky University

Figure 3. When a 122-mm projectile filled with high explosives is examined with a pulsed neutron generator, a gamma-ray spectrum taken during a neutron pulse (blue) reveals characteristic carbon, nitrogen, and oxygen peaks, while a gamma-ray spectrum taken between pulses (red) reveals hydrogen and iron peaks.

chiometric relationships to convert the elemental information to chemical assays.

In the cement industry, this information enables the optimal blending of raw materials before processing and the verification of chemical uniformity of the final product. In the coal industry, on-line measurements have found particular use in reporting the thermal energy and sulfur content of coal and for determining the fraction of the coal that is not hydrocarbon and will remain as ash after combustion. Although neutron-generator systems do not necessarily provide analytical advantages over radioisotope-based systems, they have found particular use among customers who are sensitive to radiation safety and security issues related to the use of chemical sources.

Homeland security

R&D programs at several national laboratories, universities, and private companies are investigating the development of neutron-generator-based systems for detecting high explosives, chemical weapons, and nuclear materials in a variety of objects (Figure 3). The goals of these projects include developing sensor systems for border security, airline-cargo inspection, and first response in the investigation of unknown packages.

TABLE 2. MANUFACTURERS OF COMPACT ACCELERATOR NEUTRON TUBES

UNITED STATES	**Web address**	**Primary focus**
Baker Hughes, Inc. (Houston, TX)	www.bakerhughes.com	Oilfield services
Halliburton Co. (Houston, TX)	www.halliburton.com	Oilfield services
Schlumberger Ltd. (Princeton, NJ)	www.schlumberger.com	Oilfield services
Thermo Electron Corp. (Colorado Springs, CO)	www.thermo.com	All commercial applications
INTERNATIONAL		
All-Russia Research Institute of Automatics (Moscow)	www.vniia.ru/eng/	All commercial applications
Eads Sodern (Paris)	www.sodern.com	Military and all commercial applications

The advantage of the technique over conventional approaches to dealing with unexploded ordnance, for example, lies in the ability of the system operator to perform measurements without physically touching the object being analyzed—a particularly useful feature when dealing with old, potentially unstable high explosives. The use of neutron generators for this application also has other benefits over chemical sources. They allow pulsed measurements, and they simplify safety procedures for deployment and storage because the neutron source can be turned off.

Medical studies

Another application of neutron generators is in the measurement of body composition. Techniques similar to those described above allow the measurement of the body's carbon and oxygen content with neutron inelastic scattering, and this data is used to assess the total amount and the distribution of fat in the body. This information is useful for evaluating the health of individuals with respect to obesity, aging, cardiovascular disease, and the amount of energy stored in body fat, as well as for assessing the nutritional effectiveness of different diets.

Future trends

Advances in compact sealed-tube neutron generators are focused toward the development of smaller, lighter, less expensive systems with longer lifetimes and higher outputs. Reductions in size and weight are mostly driven by the growing demand in the homeland-security market for field-portable applications, and all markets demand price, reliability, and performance improvements. Also important are ongoing advances in neutron-generator support systems, such as updating analog control systems to digital controls that incorporate advanced diagnostic routines that can be remotely accessed for wireless operation, servicing, and upgrading. Similarly, improvements in generator designs and power supplies have lowered the energy consumption of these systems to allow longer operation when working off batteries.

Particularly noteworthy advances have come in devising neutron-generator systems suitable for associated particle imaging. These generators incorporate charged-particle detectors near the target, which can record the helium atoms produced during the D–D and D–T fusion reactions. Using this information, outgoing neutrons can be identified by their emission angles and times, and used with external gamma-ray detectors and gating circuitry to acquire three-dimensional elemental information within objects (Figure 1). In the past, systems capable of generating high-resolution images were large and bulky, but newer systems are now emerging that will allow the deployment of this technique for field applications.

Further reading

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