GAO

United States Government Accountability Office
Center for Science, Technology, and Engineering
Natural Resources and Environment

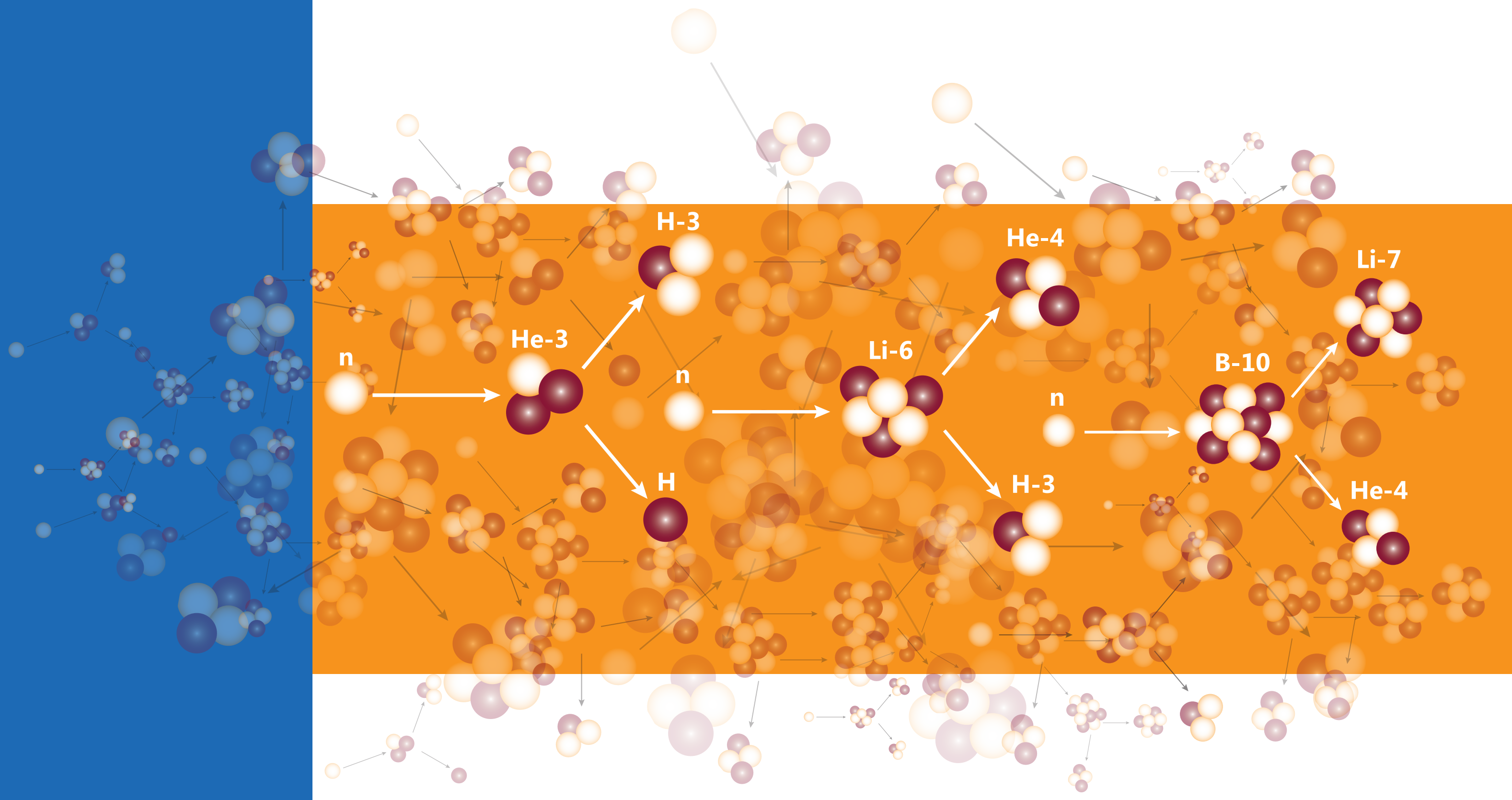
Report to Congressional Requesters

September 2011

TECHNOLOGY ASSESSMENT

Neutron detectors

Alternatives to using helium-3



GAO-11-753

Cover image from GAO represents the three neutron detection reactions that are suitable for conversion materials in neutron detectors discussed in the report. The reactions are:
n + He-3 → H-1 + H-3
n + Li-6 → H-3 + He-4
n +B-10 →Li-7* + He-4 + γ (94 percent of the time) or n + B-10 → He-4 + Li-7 (6 percent of the time)

Where:

- **n** is a neutron, depicted as a light circle in the cover image
- **H-1** is a proton, depicted as a dark circle in the cover image
- **H-3** is the hydrogen isotope hydrogen-3 (tritium) which has a nucleus containing one proton and two neutrons, depicted as a collection of three circles in the cover image, one dark circle for the proton and two light circles for the neutrons
- **He-3** is the helium isotope helium-3 which has a nucleus containing two protons and one neutron, depicted as a collection of three circles in the cover image, two dark circles for the protons and one light circle for the neutron
- **He-4** is the helium isotope helium-3 (an alpha particle) which has a nucleus containing two protons and two neutrons, depicted as a collection of four circles in the cover image, two dark circles for the protons and two light circles for the neutrons
- **Li-6** is the lithium isotope lithium-6 which has a nucleus containing three protons and three neutrons, depicted as a collection of six circles in the cover image, three dark circles for the protons and three light circles for the neutrons
- **Li-7** is the lithium isotope lithium-7 which has a nucleus containing three protons and four neutrons, depicted as a collection of seven circles in the cover image, three dark circles for the protons and four light circles for the neutrons
- **Li-7*** is the lithium isotope lithium-7 in a high energy state.
- **B-10** is the isotope boron-10 which has a nucleus containing five protons and five neutrons, depicted as a collection of 10 circles in the cover image, five dark circles for the protons and five light circles for the neutrons
- **γ** is a gamma-ray which is not depicted in the cover image

GAO

Highlights of **GAO-11-753** a report to congressional requesters

TECHNOLOGY ASSESSMENT

Neutron detectors

Alternatives to using helium-3

Why GAO did this study

Neutron detectors are used to detect neutron radiation in science, security, and other applications. For example, large-area detectors detect neutrons at science facilities across the world and radiation portal monitors screen vehicles and cargo at ports and border crossings for nuclear material that terrorists could use in a nuclear weapon. Helium-3 is a critical component of such neutron detectors, and in 2008 the U.S. government became aware of a severe shortage of helium-3 gas. While demand for it has increased, helium-3 is currently produced as a byproduct of the radioactive decay of tritium, and the United States ceased tritium production in 1988. The shortage has led science facilities and federal agencies such as the DOD and DHS to identify or develop alternative detector technologies.

GAO was asked to review the effectiveness of alternative neutron detector technologies that do not use helium-3. GAO assessed (1) what alternative neutron detectors are currently available and their effectiveness, and (2) the status of research on alternative neutron detector technologies under development for future availability. GAO reviewed agency documents and interviewed agency officials and detector developers. With assistance from the National Academy of Sciences, GAO also assembled a group of experts to review and advise on this study.

View **GAO-11-753** or key components at www.gao.gov. For more information, contact Timothy Persons at (202) 512-6412 or **personst@gao.gov** or Gene Aloise at (202) 512-3841 or **aloisee@gao.gov**

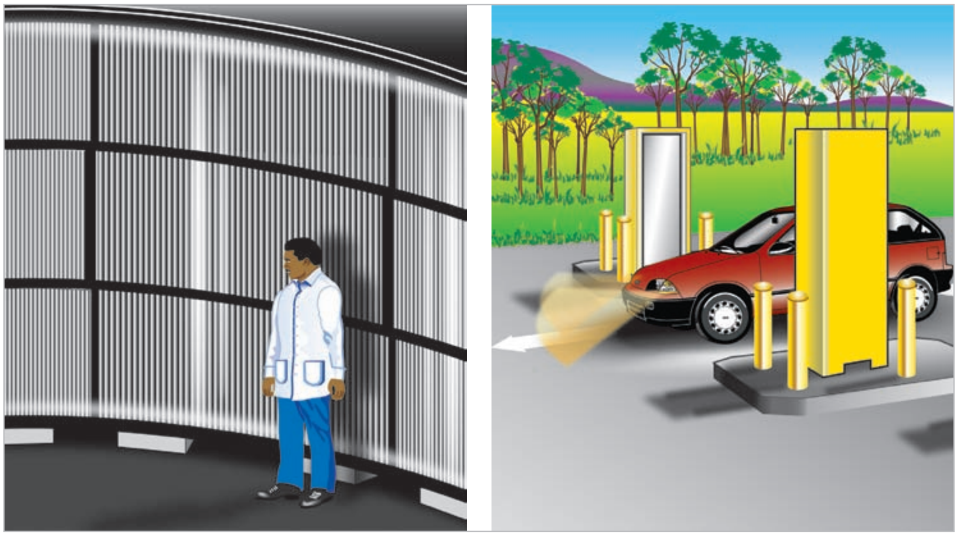
Report multimedia

Neutron detector animation:
www.gao.gov/products/GAO-11-753

What GAO found

Science facilities and federal agencies are working to determine the effectiveness of currently available alternative neutron detector technologies for use in large-area detectors and radiation portal monitors (RPM)—the two neutron detector applications that have created the greatest demand for helium-3. An international collaboration of science facilities that plan to deploy large-area detectors for research and federal agencies that procure and deploy RPMs for security have identified three alternative neutron detector technologies that are available and might satisfy requirements for use: boron-10 lined proportional detectors, boron trifluoride proportional detectors, and lithium-6 scintillators. These technologies use boron-10 and lithium-6 rather than helium-3 to detect neutrons. The international collaboration has agreed on a plan to develop and test large area detectors using these technologies. Federal agencies, such as DHS, have been directing the testing of these technologies for use in RPMs, and field testing of RPMs using boron-10 lined proportional detectors has been completed. According to agency officials, a boron-10 lined proportional detector may be available for domestic RPM deployments in early fiscal year 2012. GAO estimates this neutron detector is sufficiently mature such that a decision to use it in forthcoming portal monitor deployments can be made with confidence that the portals will perform as required. Our estimate is based on our assessment of the technology readiness levels (TRL), which assess the maturity of an application on a scale of 1 to 9. We found these three currently available alternative neutron detector technologies range in TRL from 5 to 7.

Federal agencies are funding more than 30 research and development programs that may result in additional alternative neutron detector technologies. At varying stages of research, these programs focus on security applications but may eventually be applied to other neutron detector applications. Some of these technologies may become available for integration into deployable detector systems in less than two years and could potentially help reduce demand for helium-3.



Neutron detectors: a large-area detector (left) and a radiation portal monitor (right).
Source: GAO.

We provided a draft of this report to Commerce, DOD, DOE, and DHS. They generally provided technical comments that we included as appropriate.

G A O
Accountability * Integrity * Reliability

September 29, 2011

The Honorable Donna Edwards
Ranking Member
Subcommittee on Investigations and Oversight
Committee on Science, Space, and Technology
House of Representatives

The Honorable Brad Miller
Ranking Member
Subcommittee on Energy and Environment
Committee on Science, Space, and Technology
House of Representatives

Neutron detectors are used to detect neutron radiation in science and security applications. For example, large-area detectors support materials research, and radiation portal monitors use neutron detectors to screen vehicles and cargo at ports and border crossings. Helium-3 is a critical component of neutron detectors and, in 2008, the U.S. government became aware of a shortage of helium-3 gas. Responding to your request that we conduct a technology assessment on alternative neutron detection technologies that could be used in place of neutron detectors utilizing helium-3, we assessed what alternative technologies are currently available. We also discuss the status of alternative technologies under development that may be available for future use.

As agreed with your offices, unless you publicly announce the contents of this report earlier, we plan no further distribution of it until 30 days from the report date. At that time, we will send copies to the appropriate congressional committees, Secretaries of Commerce, Defense, Energy, and Homeland Security; and other interested parties. The report will also be available at no charge on the GAO Web site at **www.gao.gov**.

If you or your staffs have any questions about this report, please contact Timothy M. Persons at (202) 512-6412 or **personst@gao.gov**, or Gene Aloise at (202) 512-3841 or **aloisee@gao.gov**. Contact points for our Offices of Congressional Relations and Public Affairs are named on the last page of the report. GAO staff who made key contributions to this report are listed on page 47.

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Abbreviations

ANSI	American National Standards Institute
ASP	Advanced spectroscopic portal
BF_3	Boron trifluoride
Commerce	Department of Commerce
DHS	Department of Homeland Security
DOD	Department of Defense
DOE	Department of Energy
DNDO	Domestic Nuclear Detection Office
Isotope Program	DOE Isotope Development and Production for Research and Applications Program
LANL	Los Alamos National Laboratory
Li-6/ZnS	Lithium-6 zinc sulfide
MRI	Magnetic resonance imaging
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NIST	National Institute of Standards and Technology
NNSA	National Nuclear Security Administration
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
SLD	Second Line of Defense
SNL	Sandia National Laboratories
SNS	Spallation Neutron Source
TRL	Technology readiness level

1 Introduction

Neutron detectors are used in research, security, and industrial applications to detect neutron radiation, a type of ionizing radiation composed of neutron particles.[1] One critical component of many such neutron detectors is helium-3 gas—a rare, nonradioactive isotope of helium that is a byproduct of the radioactive decay of tritium, a key component of the nation's nuclear weapons that is used to enhance their power (GAO 2011).[2]

Helium-3 became a favored material for neutron detectors beginning in the 1980s. In May 2011, we reported that weaknesses in the Department of Energy's (DOE) management of helium-3 delayed the federal response to a shortage of the gas in 2008.[3] The helium-3 shortage affected scientific research because, according to DOE officials, helium-3 is in great demand for large-area neutron detectors. These detectors are used for conducting materials research in medicine, energy, and transportation at facilities worldwide, including at DOE's Spallation Neutron Source (SNS).[4] The Department of Homeland Security's (DHS), Department of Defense's (DOD), and DOE's future deployments of radiation detection portal monitors, which incorporate neutron detectors, have also been affected.

Neutron detectors are used in more than 1,400 radiation detection portal monitors deployed domestically at ports and border crossings for security purposes to screen cargo and vehicles for nuclear material that terrorists might use in a nuclear weapon (GAO 2011). In 2009, DHS reported that more than 9 million containers were offloaded annually at U.S. seaports (CBP 2009), and 103 million trucks and personal vehicles entered the United States through land border crossings in 2010. In addition, neutron detectors are used overseas in about 2,000 U.S.-deployed radiation portal monitors.

Federal agencies and DOE's national laboratories are collaborating to acquire or develop alternative neutron detection technologies in order to mitigate the effect of the shortage of helium-3 on its largest consumers—large-area detectors in research facilities and radiation detection portal monitors at ports and border crossings. To support programs developing alternative neutron detection technologies and their testing, DHS, DOD, DOE, and the Department of Commerce awarded about $16 million in fiscal year 2009 and about $20 million in fiscal year 2010 to projects in industry, academia, and national laboratories. Alternative technologies could also free the limited helium-3 supply for use in

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[1] Neutron radiation is indirectly ionizing radiation—the absorption of a neutron results in the creation of ionizing particles. Ionizing radiation can damage living tissue by striping electrons from atoms, resulting in charged particles and broken chemical bonds.

[2] Isotopes are varieties of a chemical element with the same number of protons but different numbers of neutrons; for example, helium-3 has one less neutron than helium-4, the helium isotope that is commonly used in party balloons. An element's isotopes have nearly identical chemical properties, but their nuclear properties, like the ability to absorb neutrons, can differ significantly.

[3] GAO, *Managing Critical Isotopes: Weaknesses in DOE's Management of Helium-3 Delayed the Federal Response to a Critical Supply Shortage,* GAO-11-472 (Washington, D.C.: May 12, 2011).

[4] SNS, a research facility at Oak Ridge National Laboratory, includes the world's most powerful pulsed-neutron source. Constructed over 7 years at a cost of $1.4 billion, it can provide information about the structure and properties of materials that cannot be obtained by other means.

applications for which there are no helium-3 alternatives (GAO 2011).[5]

In this context, you asked us to review the availability and effectiveness of alternative neutron detector technologies that do not use helium-3. To do so, we assessed (1) what alternative neutron detectors are currently available and their effectiveness and (2) the status of research on alternative neutron detector technologies under development for future availability.

To meet these objectives, we reviewed test and evaluation documents supplied by manufacturers of neutron detection technologies and by DOE's Oak Ridge National Laboratory (ORNL) and Pacific Northwest National Laboratory (PNNL). We visited the neutron detection test facilities at PNNL, as well as SNS at ORNL, which relies on helium-3 in large-area detectors for conducting scientific research.[6] With the assistance of the National Academy of Sciences (NAS), we identified and contacted a group of experts from academia and federally funded research and development centers with a range of knowledge and expertise in technology development, nuclear physics and engineering, and neutron detector applications. These experts helped us to identify available alternative neutron detector technologies and those being developed for future use in research and security applications, as well as the considerations involved with the selection of technologies to replace neutron detectors using helium-3. This group of experts also reviewed and commented on a draft of this report. Further, we reviewed information from and interviewed officials at Commerce's National Institute of Standards and Technology (NIST), DHS, DOD, and DOE, and we contacted officials at the national laboratories involved in developing and testing neutron detectors, including DOE's Los Alamos National Laboratory (LANL), ORNL, PNNL, and Sandia National Laboratories (SNL). We interviewed representatives of companies that manufacture or research alternative neutron detection technologies. Based on available test reports, we estimated the technology readiness levels (TRLs) of the currently available alternative neutron detector technologies.[7] Section 7.1 contains additional details on our scope and methodology.

We conducted our work from July 2010 to September 2011 in accordance with all sections of GAO's quality assurance framework that are relevant to technology assessments. The framework requires that we plan and perform the engagement to obtain sufficient and appropriate evidence to meet our stated objectives and to discuss any limitations to our work. We believe that the information and data obtained, and the analysis conducted, provide a reasonable basis for any findings and conclusions in this product.

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[5] Helium-3 is also used in non-neutron detection applications. It is used in magnetic resonance imaging (MRI) to study pulmonary disorders such as chronic obstructive pulmonary disease, a lung disease in which the lungs are partially blocked, making it difficult to breathe. In this type of research, a patient inhales helium-3 during the MRI so that doctors may obtain a clear view of the entire pulmonary structure. Helium-3 is also important for scientific research involving ultra-low temperature refrigeration systems (GAO 2011).

[6] According to an ORNL official, other national laboratories also use large neutron detectors, but the SNS's planned expansion will require the construction of additional new large-area detectors in 2018.

[7] The National Aeronautics and Space Administration and the Air Force Research Laboratory use TRLs to determine the readiness of technologies to be incorporated into a specific system. Readiness levels are measured on a scale of one to nine, starting with paper studies of the basic concept, proceeding with laboratory demonstrations, and ending with a technology that has proven itself in the intended product.

2 Background

A neutron detector operates by detecting the signal generated when a neutron interacts with certain parts of the detector. Neutron detectors can be classified by how the detection process occurs. Because helium-3 has characteristics that made it effective for use in neutron detectors, it was considered a “gold-standard” for neutron detection. However, helium-3 is a rare material, and its production in the United States has been declining while its demand has been increasing, requiring helium-3 users to take action to reduce their consumption of the gas.

2.1 How neutron detectors operate

Neutron detectors operate in an environment where they may be exposed to two main types of ionizing radiation—neutron radiation and gamma radiation. Neutron radiation can be categorized as being composed of fast (higher energy) or thermal (lower energy, also known as slow) neutrons. Fission reactions and fissionable nuclear material, such as plutonium that might be used in a nuclear weapon, emit fast neutrons, while thermal neutrons result after fast neutrons have lost much of their energy by interacting with materials. Gamma radiation, which is similar to high-energy x-ray radiation and is emitted by a variety of sources, can be present where neutron detectors are used and can cause false positive results for the neutron detectors (Ginhoven et al. 2009).[8] Radiation portal monitors incorporate both gamma radiation detectors and neutron radiation detectors.

Neutron detectors can take many forms, but how they detect neutrons is generally similar. Neutrons originate from a source containing a fast neutron emitter, such as fissionable nuclear material. When some of these neutrons come in contact with a nearby neutron detector (see figure 2.1), they first strike a component of the detector called the moderator, which is designed to slow the fast neutrons so they can be more readily detected. This is an important component because neutron detectors are designed to detect thermal neutrons because the likelihood that a neutron is absorbed increases as the energy of the neutron decreases; the moderator will also absorb or reflect some neutrons. After passing through the moderator, the neutron strikes the detector component that contains a conversion material, such as helium-3.

A neutron absorption reaction takes place in the conversion material and emits energetic charged particles that interact with the rest of the detector to generate a signal, which is collected and processed to determine if it was caused by a neutron reaction or if it is a false positive due to other causes, such as background radiation (e.g., ambient gamma radiation from natural sources, such as cosmic rays or minerals in soil). Carefully designed neutron detectors can minimize the likelihood of false positive signals while maximizing the likelihood that a neutron will interact with the conversion material with detectable results. Because false positive signals often differ from a signal created by a neutron absorption reaction—for example, by being a smaller, lower amplitude signal—improved signal processing can further decrease the likelihood of false positives.

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[8] A false positive is a result that is incorrectly positive when the situation is normal. In the context of neutron detectors, a false positive occurs when a neutron detector indicates the presence of a neutron when no neutron is present.

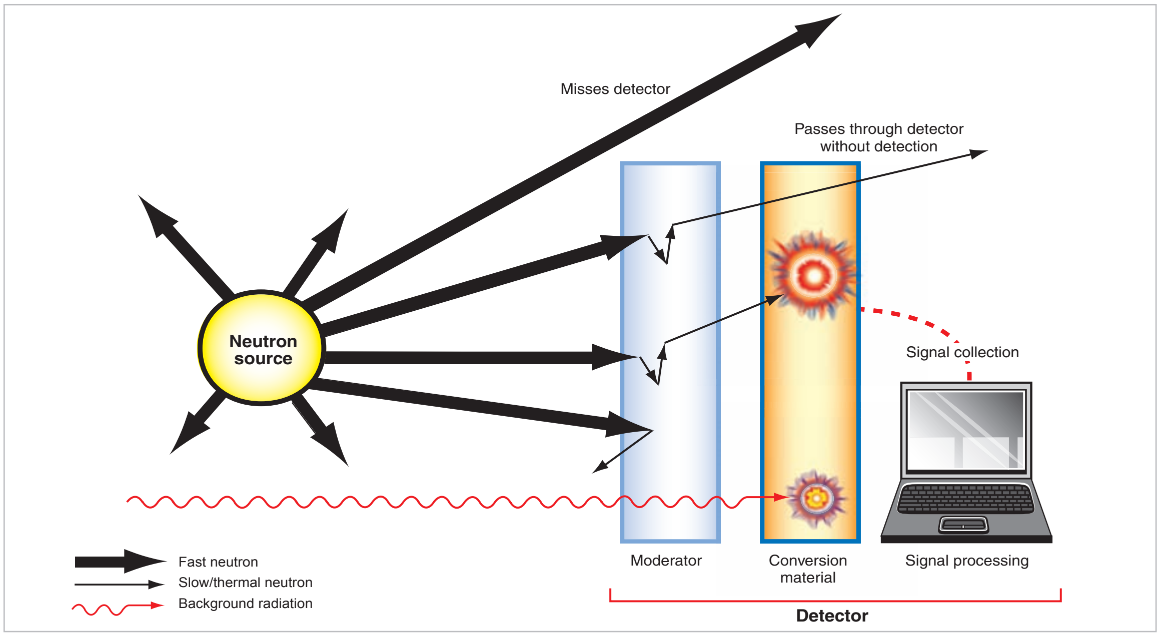

Figure 2.1 Neutron detector operation. Source: GAO.

Note: An animated depiction may be accessed at www.gao.gov/products/GAO-11-753.

2.2 Three main categories of neutron detectors

Although specific neutron detector designs can vary, based on the way in which the conversion material is arranged and how the neutron absorption reaction products are detected, they can typically be classified into one of three main categories: proportional, scintillator, and semiconductor detectors.

Proportional detectors use a gas to amplify the charge from the original charged particles generated by a neutron absorption reaction in the conversion material—the amplified charge is proportional to the original charge. A helium-3 proportional detector uses helium-3 gas as both the conversion material and for the gas amplification. Other proportional detectors use a layer of solid material as a conversion material for the detector with argon gas that provides the charge amplification. These detectors are sealed gas-filled tubes with electronic connections.

Figure 2.2 shows an example of proportional detector tubes used in large-area detectors—helium-3 tubes used in proportional detectors are commercially available in diameters from about 0.4 to 2 inches (10 to 50.8 mm) and lengths from about 2.5 to 78.5 inches (63.5 to 1994 mm).

Figure 2.2 Tubes used in a proportional detector for large-area detectors. Source: Oak Ridge National Laboratory.

Scintillator detectors use solid or liquid scintillating materials, which are materials that emit light when struck by an incoming particle. The conversion material is incorporated in the scintillator. When the conversion material absorbs neutrons, the resulting charged particles deposit energy in the scintillating material, which causes the scintillator to emit light that can be converted to an electric signal.

Semiconductor detectors consist of semiconductor chips with conversion material that can be incorporated into the chip, applied in a layer on the chip, or applied to a three-dimensional structure on the chip—these can be referred to as bulk semiconductor, coated/layered semiconductor, and three-dimensional semiconductor detectors, respectively. The charged particles from a neutron absorption reaction in the conversion material deposit energy in the semiconductor, creating an electric signal.

These three main categories of neutron detectors—proportional, scintillator, and semiconductor—can use isotopes other than helium-3 as conversion material to absorb and detect neutrons. Boron-10 and lithium-6 are the most common alternative isotopes and have higher natural abundance than helium-3. DHS considers both boron-10 and lithium-6 to be in sufficient supply for neutron detectors needed for future radiation portal monitor deployments. Furthermore, according to DOE officials, the U.S. stockpile of lithium-6 is sufficient to meet neutron detector demand and NNSA has reserved lithium-6 for detector use. Both boron-10 and lithium-6 are export-controlled materials, meaning that licenses are required when exporting boron or lithium enriched in these isotopes to certain countries. Section 7.2 has additional information about boron-10 and lithium-6.

2.3 Using helium-3 in neutron detection applications

Beginning in the 1980s, when helium-3 became available to DOE's Isotope Development and Production for Research and Applications Program (Isotope Program) to sell, demand for helium-3 for use in neutron detectors grew, partly because of the unique characteristics of detectors that use helium-3.[9] The characteristics that led these detectors containing helium-3 to become, according to experts, the "gold standard" for neutron detection include:[10]

- high neutron detection efficiency—the likelihood that a helium-3 neutron detector will absorb a neutron and produce a detection signal (Kouzes et al. 2009a);
- good gamma radiation discrimination—the ability to minimize false positives by determining whether a signal is due to neutron radiation or gamma radiation (Kouzes et al. 2009a);

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[9] The Isotope Program's mission is to produce and sell isotopes and related isotope services, maintain the infrastructure to do so, and conduct research and development on new and improved isotope production and processing techniques. The Isotope Program produces and sells about 200 isotopes, although it does not control the supply—the production or inventory—of all the isotopes it sells, such as helium-3, which is extracted from tritium by the National Nuclear Security Administration (NNSA), a semiautonomous agency within DOE. Helium-3 can be extracted from natural sources of helium gas, such as subterranean natural gas deposits, but these sources have not been pursued commercially because extracting the very low concentrations of helium-3 has not been economically viable.

[10] Other physical properties of helium-3 make it practical for other applications. For example, spin polarization of the nucleus of a helium-3 atom aligns it magnetically, making it useful in magnetic resonance imaging for lung disease research.

- nontoxicity—neutron detectors containing the nontoxic helium-3 gas do not pose a health hazard as a result of leaks of the gas (GAO 2011); and

- low cost—before the shortage, helium-3 ranged in cost from about $40 to $85 per liter, so neutron detectors containing it were low or competitive in cost compared to alternatives.[11]

One type of neutron detector that uses helium-3, the large-area detector, is used by scientific research programs. For example, at ORNL, large-area detectors at SNS are used for neutron scattering experiments and in materials research for a variety of applications. These large-area detectors typically have a surface area of about 160 to 430 square feet (15 to 40 square meters) and can each require hundreds to thousands of liters of helium-3.[12] They do not have a single set of established requirements because each detector could be unique and designed for a specific research purpose. However, an international collaboration of science facilities that builds and uses such detectors has developed guidelines for the development of large-area detectors. For example, they should be available with spatial and time resolution and be capable of operation in ultra-low temperatures and in a vacuum.[13] They should also be 70 percent efficient at detecting thermal neutrons, with gamma radiation discrimination of less than 10^{-6} (Technical Working Group 2010a).[14] Section 7.3 has additional information on neutron detector requirements.

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[11] In 2011, helium-3 bought from the U.S. government cost from $600 to $1,000 per liter. For additional information, see GAO-11-472.

[12] According to ORNL officials, SNS can contain up to 25 large-area detectors, and has a planned expansion of the facility that will require additional detectors in 2018.

[13] Spatial and time resolution describe the ability to determine where on a neutron detector a neutron is detected and when that detection occurs.

[14] Gamma radiation discrimination (or gamma radiation rejection) specifies the maximum number of gamma rays that a detector can falsely identify as neutrons. Both large-area detectors and radiation portal monitors use a requirement that the gamma radiation discrimination be less than 10^{-6}, which indicates that less than one in a million gammas can result in a false positive neutron detection.

Another type of neutron detector containing helium-3 is a component in radiation portal monitors that use the gas for security applications. These radiation portal monitors use both gamma radiation and neutron radiation detectors to scan cargo at ports and border crossings for fissionable nuclear materials and radioactive materials that may be used in nuclear weapons. Radiation portal monitors use neutron detectors to search for fast neutrons emitted by certain fissionable nuclear materials. Such nuclear materials could be shielded by water or other hydrogen-containing material in the vehicle to try to block the detection of neutrons emitted by the nuclear materials, but because neutrons are generally difficult to block, some will still reach the detector. Neutron detectors in such radiation portal monitors have a surface area of about 7.5 square feet (0.7 square meters) and require about 44 liters of helium-3 each.

Radiation portal monitors contain neutron detector components that have established requirements. These requirements define: (1) performance requirements, including specifications such as neutron detection efficiency and gamma radiation discrimination; (2) environmental requirements, specifying conditions the neutron detector must operate under (such as temperature, humidity, rain, and electric discharge); and (3) system-level requirements, specifying how the neutron detectors must work within the overall radiation portal monitor system. For example, DHS's radiation portal monitor requirements include DHS-defined requirements and incorporate standards from the American National Standards Institute (ANSI) (ANSI 2007, DHS 2010).[15]

Three primary federal agencies acquire radiation portal monitors:

- In DHS, the Domestic Nuclear Detection Office (DNDO) acquires radiation portal monitors and the U.S. Customs and Border Protection (CBP) operates them. DHS has deployed about 1,400 radiation portal monitors and is currently revisiting the additional number needed; it had plans to deploy about 700 more through 2015 to scan vehicles and cargo at domestic ports and border crossings.[16]
- In DOE, the Second Line of Defense (SLD) program acquires radiation portal monitors and deploys them overseas to be operated by the host countries. According to DOE officials, SLD has deployed about 2,000 radiation portal monitors and plans to deploy about 2,900 more through 2018 to scan cargo at ports overseas.[17]
- In DOD, the Guardian program acquires radiation portal monitors to scan vehicles and cargo entering some military facilities.

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[15] ANSI, a private, not-for-profit organization with private and government membership, oversees the creation and use of a variety of consensus standards.

[16] A variant of radiation portal monitors, the Advanced Spectroscopic Portal (ASP) is designed to identify the material producing radiation. According to July 2011 congressional testimony by the director of DNDO, the ASP program will end as originally conceived. Of the existing ASP systems, 13 will be deployed to ports of entry to gain operational familiarity with the systems and to gather data in support of a future acquisition program.

[17] DOE deploys radiation detection equipment at overseas facilities as part of its Second Line of Defense program and Megaports Initiative to assist foreign governments in combating nuclear smuggling (GAO 2006).

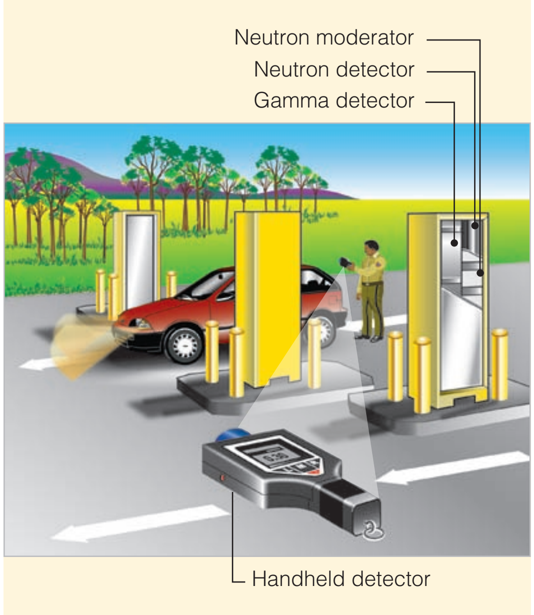

Figure 2.3 Neutron detectors—radiation portal monitors and a handheld detector. Source: GAO.

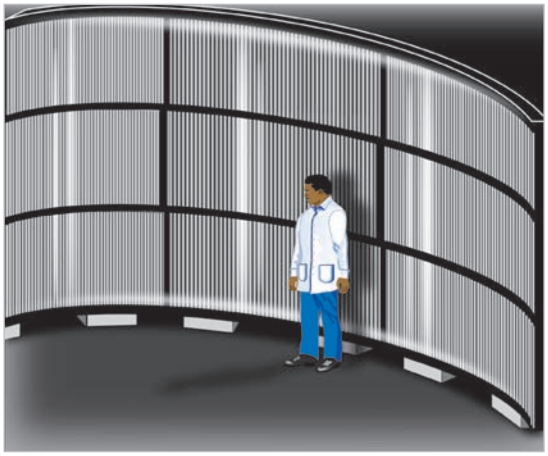

Figure 2.4 Neutron detectors—a large-area detector. Source: GAO.

According to DOD officials, as of March 2011, Guardian had deployed 24 radiation portal monitors that use helium-3 and had plans to deploy an additional 12, using an alternate neutron detector technology, to military facilities worldwide.

Besides large-area detectors and radiation portal monitors, neutron detectors using helium-3 are used in several other applications. Smaller and intermediate-sized detectors, such as handheld and backpack detectors, are used for mobile security-related applications. Each of these detectors uses a small quantity of helium-3, as compared to radiation portal monitors, with a total projected annual demand across the U.S. government of about 7,000 liters of helium-3 from 2011 to 2015. Industrial uses include measuring the moisture content in rock and soil to support activities like road construction. The oil and gas industry uses neutron detectors in exploratory drill shafts to determine the likelihood of oil or gas. Annual demand for helium-3 for moisture gauges is estimated at about 500 liters, and annual demand for oil and gas exploration is estimated at about 1,000 liters. Figure 2.3 and Figure 2.4 illustrate the relative scales of different neutron detectors.

2.4 Production of and demand for helium-3

Helium-3 is a rare isotope of helium; naturally occurring helium-3 constitutes a few parts per million of helium gas (the rest of the helium gas is composed of the common helium-4 isotope) (Coursey et al. 2010). Today's U.S. supply of helium-3 comes from the radioactive decay of tritium[18] in the U.S. tritium stockpile, which is maintained by the National Nuclear Security Administration (NNSA).[19] Helium-3 can also be extracted from natural sources of helium gas, such as subterranean natural gas deposits, but these sources have not been pursued commercially because extracting the very low concentrations of helium-3 has not been economically viable.

Until 1988, tritium was manufactured to support the U.S. nuclear weapons program because it is a key component used to enhance a weapon's power. In maintaining the tritium stockpile, NNSA removes the helium-3 that accumulates as tritium decays, because the helium-3 can diminish the effectiveness of the nuclear weapons. In the past, NNSA and its predecessor agencies considered helium-3 to be a waste product of the weapons program and vented it to the atmosphere, but from about 1980 through 1995, and again from 2003 through 2008, those agencies provided helium-3 to DOE's Isotope Program to sell.[20] The minimum price for helium-3 was set to recover the cost of extracting it from the tritium and the administrative cost of selling it, which until 2009 typically ranged from $40 to $85 per liter.

Since the end of the Cold War, the United States has been reducing its nuclear weapons stockpile, resulting in less tritium and, therefore, less helium-3. Meanwhile, demand for helium-3 rose over the past 10 years primarily because it was used increasingly in neutron detectors for research and security applications. In 2008, the U.S. government abruptly learned that it faced a severe shortage of helium-3 because of this reduction in supply and increase in demand. In 2009, the National Security Staff established an interagency policy committee consisting of officials from Commerce, DHS, DOE, and the Department of State to address the helium-3 shortage.[21] This policy committee established criteria and a process for allocating the limited supply of helium-3 to government and non-government customers, reducing the amount of helium-3 available for large-area detectors and radiation portal monitors.[22] According to officials, SNS, which has plans to expand in 2018 by adding a second instrument hall, will be able to support about 25 additional large-area

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[18] Tritium, an isotope of hydrogen, radioactively decays into helium-3 at an annual rate of 5.5 percent For further information about triitium production, see GAO, *Nuclear Weapons: National Nuclear Security Administration Needs to Ensure Continued Availability of Tritium for the Weapons Stockpile*. GAO-11-100 (Washington, D.C.: October 7, 2010.

[19] Congress created NNSA as a semiautonomous agency within DOE under title 32 of the National Defense Authorization Act for Fiscal Year 2000 (Pub. L. No. 106-65, § 3211, 113 Stat 512. 957 (1999)). NNSA is responsible for the management and security of the nation's nuclear weapons, nonproliferation, and naval reactors programs.

[20] The Isotope Program did not sell helium-3 from about 1995 through 2001 because helium-3 was being stockpiled for use in NNSA's Accelerator Production of Tritium project. During this time, Russia was the primary source of commercially available helium-3. In 2003 NNSA and the Isotope Program signed a Memorandum of Understanding to make available for sale, from 2003 to 2008, about half of NNSA's estimated helium-3 inventory.

[21] The National Security Staff, established under and reporting to the National Security Advisor, supports all White House policymaking activity related to international and homeland security matters.

[22] Applications for which there is no alternative to helium-3 receive the highest priority for helium-3 allocations, followed by programs for detecting nuclear material at foreign ports and borders, followed by programs for which substantial costs have already been incurred.

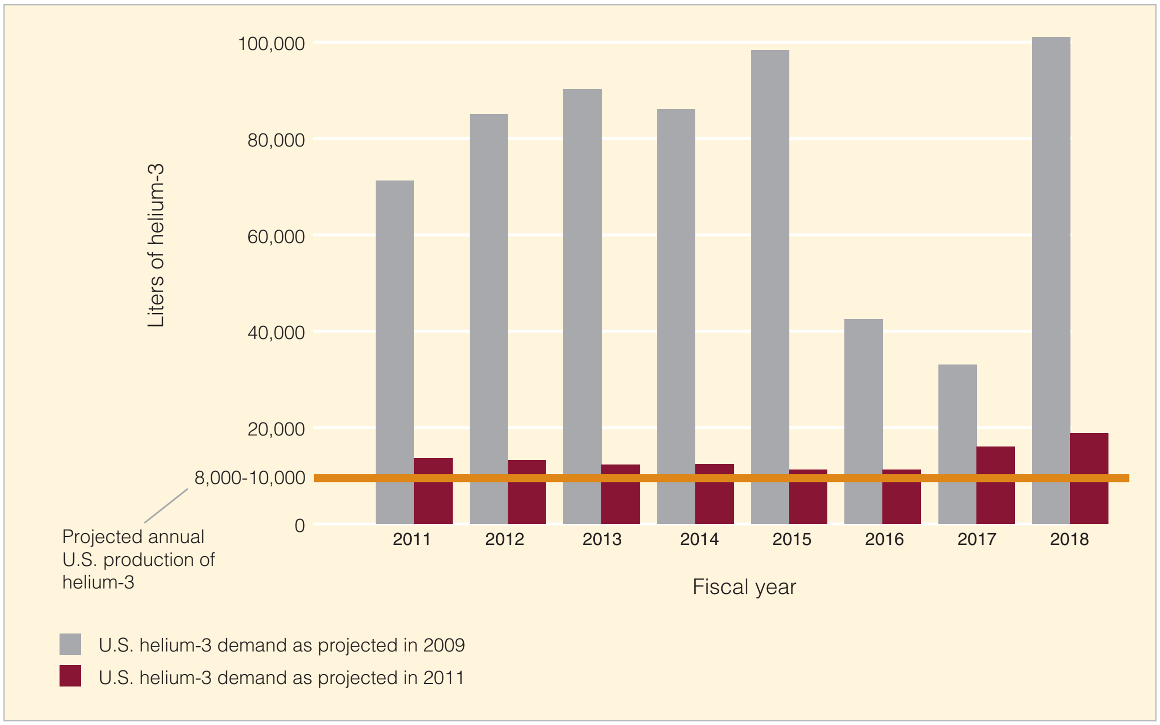

Figure 2.5 Helium-3 demand and annual U.S. production, 2011–18, as projected in 2009 and 2011. Source: GAO analysis of information from the interagency policy committee.

detectors; alternative neutron detectors will be needed for these new detectors. Radiation portal monitor deployments have not yet been affected by the helium-3 shortage, as according to agency officials, DHS and DOE have sufficient radiation portal monitors using helium-3 awaiting deployment to maintain their deployment plans through 2011 and 2013, respectively, and DOD's Guardian—a relatively small radiation portal monitor program—has also met its deployment plan.

NNSA estimates that it will make available about 8,000-10,000 liters of helium-3 per year for distribution, less than the demand created by neutron detectors and other applications. To address this shortage, the policy committee eliminated allocations of helium-3 for domestic radiation portal monitors beginning in fiscal year 2010 because, according to committee documents, it had determined that alternatives to helium-3 for neutron detectors in radiation portal monitors would suffice (GAO 2011). To further address this shortage, 10 research facilities around the world (including DOE's SNS and several facilities in Europe and Japan) that have plans to deploy large-area detectors to support their research programs have agreed to form an international collaboration to coordinate their development of alternative detectors using a multi-year development and testing plan.[23] The

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[23] In 2010, an international group of 10 research facilities that use large-area detectors agreed to collaborate in the development of alternative neutron detectors. They include the Neutron Science Directorate at ORNL (which includes SNS) and the NIST Center for Neutron Research in the United States, the Japan Proton Accelerator Research Complex (J-PARC), the Julich Centre for Neutron Science in Germany, and the Paul Scherrer Institute in Switzerland.

Figure 2.6 Helium-3 demand by application, 2011-18, as projected in 2011. Source: GAO analysis of information from the interagency policy committee.

two U.S. member facilities of this international collaboration—NIST and ORNL—are conducting some testing of alternative detectors and will likely benefit from the knowledge gained from the testing conducted at other facilities.

The policy committee's allocation process, along with efforts by the international collaboration of neutron science facilities, has reduced the projected demand for helium-3. Figure 2.5 illustrates the total estimated demand for helium-3 as projected in 2009, before steps were taken to reduce demand, and as projected in 2011, after the policy committee and others took measures to better align demand for helium-3 with its available supply. The substantial difference between the helium-3 demand projections in 2009 and 2011 is largely based on the assumed availability of alternative neutron detector technologies used for neutron detectors in large-area detectors (for science) and radiation portal monitors (for security).

Projected demand still exceeds the expected annual U.S. production of helium-3, but some inventory of the gas remains—about 31,000 liters in February 2011, but the amount changes daily—and the feasibility of utilizing other sources of helium-3 is being explored by U.S. agencies (GAO 2011). Figure 2.6 illustrates the projected demand for helium-3 by application category, as projected in 2011—because the interagency policy committee had eliminated allocations of helium-3 for domestic radiation portal monitors beginning in fiscal year 2010, the demand for helium-3 in figure 2.6 does not include demand due to radiation portal monitors.

3 Alternative neutron detector technologies are currently available

Three different neutron detector technologies are currently available that utilize different technologies and different isotopes, and additional testing is being performed to determine their effectiveness at meeting the requirements for use in large-area detectors and radiation portal monitors. We determined the maturity of these technologies for use in radiation portal monitors by reviewing the available test results and estimating the TRLs of these technologies.

3.1 Three current alternative technologies may meet requirements for large-area detectors and radiation portal monitors

Three alternative neutron detector technologies, currently available and in use for other detector applications, were identified by agency officials and experts as potentially meeting the requirements for large-area detectors and radiation portal monitors, although they have not yet been fully tested for these applications. The three technologies—boron-lined proportional detectors, boron trifluoride (BF_3) proportional detectors, and lithium-6 scintillators—have characteristics similar to helium-3 detectors, based on testing done to date. Each is described in table 3.1 and in the text below.

3.1.1 Boron-lined proportional detectors

Several vendors produce boron-lined proportional detectors with different designs, but they are all sealed tubes with boron-10 placed in a thin layer on the interior surface of the tube to form the conversion material; the tube is then filled with a mix of gases. Similar to helium-3 tubes, these tubes are typically less than 1 to 2 inches in diameter (25.4 to 50.8 mm) and have an appearance similar to those depicted in figure 2.2. A variation of this technology, known as boron-lined straw tubes, uses thin tubes with very small diameters (about 1/6 inch, or 4.2 mm). The boron-lined proportional detector tubes typically are about 10 to 15 percent as efficient at detecting neutrons as a helium-3 tube. Boron-lined tubes are used in arrays of tubes to achieve detector efficiency comparable to a neutron detector using a single helium-3 tube. (Ginhoven et al. 2009; Kouzes et al. 2010a; Woodring et al. 2010)

The international collaboration of science facilities has identified boron layer detectors—of which boron-lined proportional counters are a type—as an alternative neutron detector technology that could be tested and used for large-area detectors by 2014. It notes that the boron-lined straw tubes are promising but expensive, although options may exist for making them more cost-effective. One of the international collaboration's working groups is looking at a variety of configurations for Boron-lined counters and will be studying different coating techniques, tube shapes and sizes, and performance characteristics (Technical Working Group 2010b).

Technology	Expected cost[a]	Meets required detection efficiency?[b]	Meets required gamma radiation discrimination?[c]	Factors to consider
Boron-lined proportional detectors	High	Yes	Yes	Boron-10 is an export controlled material
Boron trifluoride (BF_3) proportional detectors	Low	Yes	Yes	Hazardous material
Lithium-6 scintillators	High	Yes	Yes	Lithium-6 is an export controlled material

Table 3.1 Key characteristics of alternative neutron detector technologies for use in radiation portal monitors. Source: GAO analysis of agency documents and test results from national laboratories.

Note: This table addresses tests using a particular technology as incorporated into a radiation portal monitor system and does not address testing in non-portal monitor systems, such as vehicle-portable or backpack neutron detectors.

[a] For the purposes of this comparison, the cost of acquiring a single neutron detector module for one radiation portal monitor panel was considered, with "low cost" being less than $15,000, and "high cost" being more than $15,000, based on estimates provided by detector manufacturers and by DHS officials. This cost comparison does not include any potential differences in lifecycle costs due to maintenance, safety, etc.

[b] Required detection efficiency for neutron detectors in radiation portal monitors is 2.5 counts per second per nanogram of Californium-252 in a defined testing geometry.

[c] Required gamma radiation discrimination in radiation portal monitors is 10^{-6} in a defined gamma radiation field.

3.1.2 Boron trifluoride gas proportional detectors

Boron trifluoride (BF_3) gas is composed of fluoride atoms and boron atoms—the boron in BF_3 is enriched in boron-10, which allows BF_3 to be used as a conversion material. BF_3 gas proportional detectors were widely used as neutron detectors before helium-3 became a commonly used conversion material, but they would still require testing in specific systems for large-area detectors and radiation portal monitors. BF_3 proportional detectors are similar in construction to helium-3 proportional detectors, but contain BF_3 gas instead of helium-3 gas. According to test results, BF_3 tubes are about 30 to 50 percent as efficient at detecting neutrons as helium-3, but multiple tubes can achieve the desired detector efficiency, and BF_3 detectors can provide better gamma discrimination than helium-3 detectors (Knoll 2000; Kouzes et al. 2009b). These tubes have an appearance similar to the detector tubes shown in figure 2.2.

Neutron detectors using BF_3 are the least expensive of the three alternatives for acquisition purposes, but BF_3 is a toxic material that must be handled and shipped in accordance with Department of Transportation regulatory requirements.[24] Industry representatives and national laboratory scientists have expressed concern about its use, because of both the transportation issues entailed in regulatory requirements and possible exposure to the public in the event of a leak. While a sealed BF_3 tube would pose little risk by itself, damage to the tube could result in a leak of the toxic material, although the tubes are filled to slightly less than atmospheric pressure, potentially mitigating the effects of a leak.

The international collaboration of science facilities has identified BF_3 as the “most direct and probably the fastest way” to replace helium-3 in large area detectors and expressed concern about its toxicity (Technical Working Group 2010a).[25] According to an international collaboration document, the collaboration is exploring the safety requirements associated with using BF_3 in detectors, in addition to whether the detectors can provide adequate spatial resolution.

Concern about the toxicity of BF_3 may limit its use in radiation portal monitors because of potential exposure of the public to BF_3 in the event of a leak—one vendor has rejected the use of BF_3 for use in radiation portal monitors because of such concerns. According to DNDO, to support the evaluation of all possible alternatives, the agency is supporting work to improve radiation portal monitor designs to mitigate the risks of a BF_3 leak from a radiation portal monitor. For example, a DNDO requirements document stated that the hazards posed by BF_3 could be mitigated by requiring that a radiation portal monitor using BF_3 should have multiple layers of containment, material to absorb the gas in the event of a leak, and an improved detector housing to minimize the likelihood of a leak (DHS 2010). A decision to use BF_3 in radiation portal monitors will need to consider the risks associated with using it, as well as any increased costs associated with implementing additional safeguards and compliance with regulations governing BF_3 handling and shipping.

3.1.3 Lithium-6 scintillator detectors

Several vendors produce lithium-6 scintillators with different designs. One type uses lithium-6 zinc sulfide (Li-6/ZnS) scintillating material coated on fiber optics. In this design, an incoming neutron is absorbed by the lithium-6, creating charged particles that generate light in the scintillating material that is then detected by photo-detectors via the fiber optics (Kouzes et al. 2010b). The photo-detectors generate a signal that undergoes signal processing to determine the source of the scintillation light. The other type of lithium-6 scintillator uses lithium-6 embedded directly into a scintillating glass fiber (Ginhoven et al. 2009). Figure 3.1 shows a detector panel under construction with these fibers arranged in a flat sheet for use in a large-area detector, which requires spatial resolution. These types of detectors, when assembled for use in detectors

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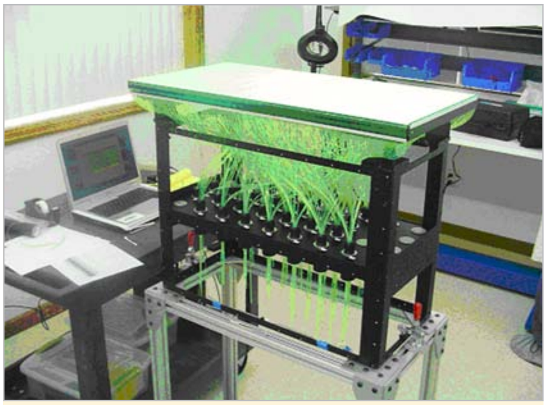
[24] Exposure to boron trifluoride can irritate or burn the skin and eyes. Inhalation can result in irritation of the upper respiratory tract or inflammation of the lungs, with potential chest pain and difficulty breathing.

[25] This proposal was authored by an international technical working group, assembled in response to a meeting of science facility directors in 2009, and is one document guiding the international collaboration in its work to develop alternative detector technologies for large-area detectors.

that do not require spatial resolution, such as radiation portal monitors, will be simpler in design than the panel in figure 3.1, because a grid of fibers will not be necessary.



Note: This detector module is for use in a large-area detector and provides spatial resolution by creating a grid of fibers; the location of a neutron absorbed by this detector will therefore be known by identifying which fiber scintillates.

Figure 3.1 A Li-6/ZnS scintillator detector module for SNS. Source: Oak Ridge National Laboratory.

3.2 Testing process for the three alternative technologies for use in large-area detectors

The international collaboration of science facilities agreed upon a development and test process that will determine the suitability of alternative detector technologies for large-area detectors. The participating U.S. organizations are supporting the collaboration's work with boron-lined proportional detectors and lithium-6 scintillators. According to collaboration planning documents, the knowledge gained by those efforts and by work done by the other members of the international collaboration will help inform both large-area detector design and the design of smaller research-oriented neutron detectors using alternative technologies. According to the collaboration planning documents, NIST will be examining some of the light detection equipment used in lithium-6 scintillator detectors, and ORNL will be developing a lithium-6 detector and will test the performance of a boron-10 lined straw tube detector (Technical Working Group 2010b). Because of the unique nature of each large-area detector and the long design process associated with building such detectors, the planning documents indicate that this process will continue for the next several years and will involve the development of demonstration detectors using each currently available alternative technology under consideration (Technical Working Group 2010a):

- Boron-lined proportional detectors—the international collaboration plans to demonstrate that boron-10 detectors can perform nearly as well as helium-3, to optimize the design and fabrication of boron-10 detectors, and to demonstrate the feasibility of large scale detectors. International collaboration members reported that one small demonstrator detector using boron-lined proportional detectors is now being built and that they anticipate that more complete demonstrator detectors may become available from March 2012 to March 2014 (Technical Working Group 2010a).

- Boron triflouride proportional detectors—the international collaboration plans to explore how to build and operate BF_3 detectors in compliance with safety rules, to assess their performance, and to build and evaluate a full-scale demonstrator detector. The international collaboration plans to have a large-area prototype, with demonstration tests, by March 2012 (Technical Working Group 2010a). According to a member of the international collaboration, current testing of a prototype shows that BF_3-based positional sensitive detectors have proper position resolution, gamma discrimination, and theoretical detection efficiency.

- Lithium-6 scintillators—the international collaboration identified scintillators with fiber optic light guides as a potential replacement technology, and collaboration member facilities will conduct testing to determine the suitability of lithium-6 scintillators. The collaboration has several concerns about these scintillators—for example, gamma radiation discrimination may not be good enough, and the detector may not be able to count neutrons at a high enough rate. Furthermore, the materials used may not be suitable for the vacuum environment experienced by large-area detectors, and the high cost of these detectors remains a concern. The international collaboration plans for 2 to 2-1/2 years of detector development and evaluation in the participating facilities, with as much as another year to conduct another iteration of evaluation for the detectors if needed, with a final year to transfer techniques to industry, for a total of 3 to 4-1/2 years (Technical Working Group 2010a).

According to SNS officials, because the helium-3 shortage occurred after the construction of SNS's large-area detectors was completed or well under way, SNS does not have an immediate need for additional helium-3; however, a planned SNS expansion will need alternative neutron detectors in 2018. Some new large-area detectors may use alternative technologies rather than helium-3; the planned development and testing of these alternative technologies can provide additional information regarding the characteristics of the alternatives, informing decisions on what technology to utilize. This testing appears to be appropriate to help mitigate the effects of the shortage on U.S. neutron science efforts—any new detectors that can utilize an alternative technology will help reduce demand for helium-3. Other detectors may have requirements for very high neutron detection efficiencies that can only be satisfied by using helium-3. In such cases, a decision to use the limited supply of helium-3 for these detectors or to accept reduced performance using an alternative technology will need to be made based on the anticipated costs and benefits of each option.

3.3 Testing process for the three alternative technologies for use in radiation portal monitors

According to officials from the acquisition agencies (DNDO, DOE, and DOD), the suitability of alternative technologies for radiation portal monitors will be determined by a series of tests the acquisition agencies will conduct. This process, as DNDO describes it, is outlined in figure 3.2 and in the text below.

After a vendor develops and tests a detector, DNDO may direct certain national laboratories (or other laboratories qualified to do so) to conduct performance testing, verifying that the detector satisfies performance requirements (described in section 7.3). If the performance testing is successful, the laboratories will then conduct environmental and system integration testing to verify that the other requirements are satisfied. The government then field tests the radiation portal monitors using the alternative neutron detector. Depending on when in this process DNDO makes an acquisition decision, these tests may be used to inform an acquisition or as acceptance testing for radiation portal monitors following the acquisition.

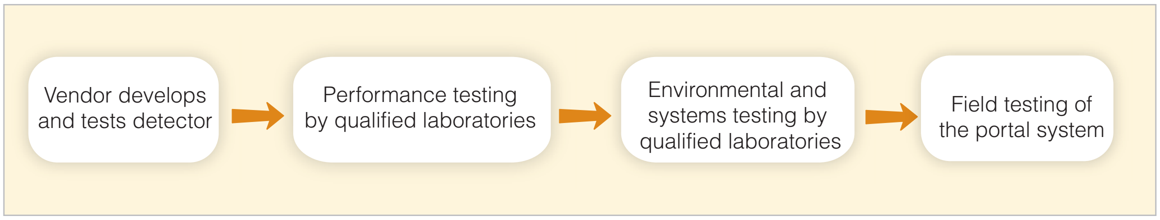


Figure 3.2 DHS's steps to test radiation portal monitors using alternative neutron detectors. Source: GAO analysis of DNDO information.

Boron-10 lined proportional detectors, BF_3 proportional detectors, and lithium-6 scintillators have undergone performance testing at PNNL, according to testing documents (Kouzes et al. 2009b; Kouzes et al. 2010a; Kouzes et al. 2010b). Furthermore, DNDO awarded contracts to five vendors in February 2011 to acquire radiation portal monitors using alternative neutron detectors—of these five vendors, one uses boron-10 lined straw tubes as its alternative neutron detector technology and the four others use lithium-6 scintillators of varying designs. DNDO is conducting performance tests and limited environmental tests on these detectors in 2011.[26] In a separate effort, DNDO has completed performance, environmental, and systems tests for one radiation portal monitor design using a boron-10 lined proportional detector, and completed field testing of this design in July 2011. Preliminary results of the field tests indicate this radiation portal monitor design successfully passed all test objectives and, according to agency officials, DNDO anticipates having this alternative available for deployment in early fiscal year 2012.

DOD's Guardian program, which deploys radiation portal monitors to scan vehicles and cargo entering military facilities, directed PNNL to verify the vendor-reported performance of one radiation portal monitor using a boron-10 lined proportional detector, according to DOD officials. DOD acquired 12 of these radiation portal monitors and, and according to these officials, plans to conduct field tests during deployment in 2011.

DOE's SLD program, which deploys radiation portal monitors overseas to help prevent nuclear smuggling, is currently proceeding to acquire radiation portal monitors that use alternative neutron detectors (GAO 2011; GAO 2006). According to DOE officials, as part of the procurement, prototypes will undergo performance tests at a national laboratory. Following award of the contract but prior to deployment of the radiation portal monitors, they will undergo exhaustive testing at a national laboratory.

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[26] At this stage in DHS's testing process, these prototypes did not undergo complete testing of the environmental requirements. They were tested over specified humidity and temperature ranges, with exposure to temperate and freezing rain, with a physical impact, and with exposure to an electrostatic discharge. They have not yet been tested for other environmental requirements, such as exposure to external electromagnetic fields, operation during and after vibrations, and operation during and after exposure to blowing sand.

3.4 Maturity of radiation portal monitors using the three alternative detector technologies

To determine the maturity of radiation portal monitors using the currently available alternative neutron detector technologies, we have estimated the TRL for radiation portal monitors using each technology. TRLs are commonly used to assess the maturity of a technology for a specific application (see section 7.4 for additional details on TRLs) and range from TRL 1 to TRL 9: TRL 1 indicates a technology for which only the basic principles have been observed, and TRL 9 indicates a technology fully integrated into a system that has been fully tested and demonstrated through successful operational use. A higher TRL indicates a system has better demonstrated suitability relative to a specific set of criteria, and a decision to proceed with an acquisition of the system will accordingly be lower risk. According to DNDO officials, radiation portal monitors using alternative neutron detectors will typically be transitioned to an acquisition group when the radiation portal monitors are at TRL 6 to 7.

To estimate the TRLs, we used the TRL scale developed by the National Aeronautics and Space Administration (NASA) (NASA 2008). We use this scale because the NASA scale is the basis for other TRL scales, such as DOD's TRL calculator. Furthermore, according to DNDO officials, a research directorate in DNDO typically uses the NASA TRL scale when it performs TRL assessments. Our TRL estimates are based on assessing the quality of the radiation portal monitor test objects containing alternative neutron detectors and comparing the performance of the test objects to DNDO radiation portal monitor requirements, using the current status of testing of alternatives for radiation portal monitors. These estimates do not represent the TRLs for each technology when integrated into other neutron detector systems, such as portable handheld or backpack detectors. Table 3.2 summarizes the testing that has been completed for radiation portal monitors.

- Boron-lined proportional detectors—based on performance testing of prototypes from multiple vendors at PNNL, this detector technology can provide the required sensitivity and gamma radiation discrimination. A prototype from one vendor passed DNDO performance tests and limited environmental tests in summer 2011. Another vendor has produced a radiation portal monitor that is a finalized production model that, at the direction of DNDO, has passed all performance, environmental, and systems testing and has completed field testing in its intended operational environment (a CBP port of entry). As a result, we estimate this radiation portal monitor using a boron-lined proportional detector is at a TRL 7 and could advance to TRL 8 upon successful completion of field tests.[27] Upon reaching TRL 8, this radiation portal monitor will have been proven to work in its final form and under expected conditions and could be acquired for deployment with reduced risk.

- Boron triflouride gas proportional detectors—based on performance testing conducted at PNNL, BF_3 proportional detectors can provide a suitable replacement for helium-3 proportional detectors for radiation portal monitors. However, full tests of a BF_3 radiation portal monitor prototype are still needed—for example, environmental and

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[27] While these field tests have been completed, the test results have not yet been made available..

Technology	Performance testing by qualified labs	Environmental and systems testing by qualified laboratories	Estimated technology readiness level (TRL)[a]
Boron-lined proportional detector	Production models satisfied DHS performance requirements in 2010	Full environmental and systems tests completed at national laboratories in 2011	7
Boron trifluoride gas proportional detector	Laboratory prototypes satisfied DHS performance requirements in 2009	None	5
Lithium-6 scintillator	Production prototypes satisfied DHS performance requirements in 2011	Production prototypes satisfied limited environmental requirements in 2011[b]	6

Table 3.2 Testing of radiation portal monitors using alternative neutron detector technologies. Source: GAO analysis of testing conducted by ORNL and PNNL.

Note: This table addresses tests using a particular technology as incorporated into a radiation portal monitor system and does not address testing in non-portal monitor systems, such as handheld or backpack neutron detectors. The test status is based on the particular design in each technology type that has successfully undergone the most testing.

[a] TRLs based on the neutron detector prototype with the highest TRL in each technology classification.

[b] Limited environmental tests: temperature, humidity, temperate and freezing rain, microphonics and impact, and electrostatic discharge

systems testing—and BF_3 radiation portal monitors have yet to demonstrate performance under operational conditions. BF_3 proportional detectors, while generally considered a mature technology for other detector applications, have not been integrated into mature prototypes of radiation portal monitors, and their testing for use in radiation portal monitors has demonstrated only basic performance capabilities. We estimate radiation portal monitors using BF_3 proportional detectors are at a TRL 5 for use in radiation portal monitors; they could advance to higher TRLs upon the completion of additional testing and the development of a more mature prototype.

- Lithium-6 scintillator detectors—based on performance testing of prototypes from multiple vendors at PNNL, some of the tested systems can provide the required neutron detection efficiency and gamma radiation discrimination. Prototypes from three different vendors passed DHS performance tests and limited environmental tests in summer 2011. We estimate these radiation portal monitors using lithium-6 scintillators are at a TRL 6 and could advance to a TRL 7 upon the successful completion of testing in an operational environment. Based on the duration of testing of the boron-lined proportional detector that recently completed field tests, if DNDO decides to direct one of these prototypes to complete the remainder of the environmental tests and to undergo systems tests, such tests could require less than four months.

According to DNDO, and supported by the testing of radiation portal monitors using alternative neutron detectors, it appears that a boron-10 lined proportional detector will be available for use in early fiscal year 2012. BF_3 detectors are under development at national laboratories at the direction of DNDO, but no vendor has yet made a prototype available for test and evaluation. Lithium-6 scintillator detectors may be available later in fiscal year 2012.

4 Additional neutron detector technologies are being developed

Four federal agencies are funding research and development projects to develop alternative neutron detector technologies. According to agency officials and documents from the interagency policy committee formed to address the helium-3 shortage, Commerce, DNDO, DOD, and DOE are coordinating more than 30 different research and development projects in industry, academia, and national laboratories that may result in alternative technologies for neutron detection applications—funding for these projects was about $20 million in fiscal year 2010. Agency documents indicate that some of these alternative technologies may be sufficiently advanced with laboratory tests to begin integration into prototype detector systems in less than two years, with deployable detector systems following the integration of these technologies.

These agency-funded projects are not limited to developing alternative neutron detectors for radiation portal monitors—they are also developing neutron detectors for use in smaller, portable detectors, such as handheld or backpack detectors, to further reduce demand for helium-3. Because the agencies are developing technologies for security applications that could have overlap in research program goals, they are acting to reduce duplication of effort by formally coordinating the research and development projects through the interagency policy committee by sharing information on the projects each agency is funding. According to agency officials, there is also informal coordination through contact between program managers at each agency.

Our review of agency documents for these federally funded programs indicates that these research projects are working to improve the performance of existing technologies or to develop new forms of scintillator and semiconductor technologies, as well as to develop new neutron detector technologies that do not fit within these categories. Table 4.1 provides examples of some of the technologies being developed.

For scintillator detectors, some research and development projects are focused on optimizing the more mature technologies, like DOD and DNDO projects supporting the improvement of lithium-6 scintillators. Other programs are working toward developing new scintillator materials, like the DNDO-supported work on CLYC crystals.[28] The development of new scintillator materials includes exploring families of materials for scintillation properties, identifying detection capabilities, and developing techniques to fabricate the materials in quantities sufficient to support the development of prototype detectors.

For semiconductor detectors, research and development projects are working to improve detection efficiencies and fabrication techniques. Coated/layered semiconductors, consisting of a layer of conversion material on an electronic chip, have neutron detection efficiencies that are usually low compared to other types of detectors—projects looking to improve semiconductor neutron detectors can improve

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[28] CLYC (Cs_2LiYCl_6) scintillating crystals detect both neutrons and gamma radiation, which would normally limit a neutron detector's effectiveness because of poor gamma discrimination. However, neutrons and gamma radiation create different kinds of signals from the CLYC crystal, allowing it to function as an effective neutron detector.

Detector type	Technology program[a]	Research stage[b]	Potential security application[c]	
			Portal	Portable
Scintillator	Sodium iodide or cesium iodide scintillators with lithium-6	Early	✓	✓
	Zinc oxide with lithium-6, boron-10, or gadolinium coatings	Early	✓	✓
	CLYC (Cs_2LiYCl_6:Ce) scintillator crystals	Late		✓
Semiconductor	Boron triselenide (B_2Se_3)	Late		✓
	Lithium-6 semiconductor compounds	Early		✓
	Boron loaded 3-D pillar and trench structured semiconductors	Late	✓	✓
Other[d]	Water-based detector	Mid	✓	
	Noble gas excimers	Mid	✓	✓

Table 4.1 Examples of alternative neutron detector technology programs. Source: GAO analysis of information from the interagency policy committee.

[a] Examples are selected to convey the range of technologies under development and should not be taken to be the most advanced or promising technologies under development.

[b] "Research stage" estimates how advanced the research and development program is, based on information from the funding departments through the interagency policy committee. "Late" indicates the technology may become available for integration into detector systems in less than 3 years; "Mid", 3–5 years; "Early", more than 5 years.

[c] Potential applications are limited to radiation portal monitors and portable detectors (handheld or backpack) because the funding agencies generally support neutron detector development for security applications. Information for "Potential application" is from the funding departments through the interagency policy committee.

[d] "Other" indicates these programs are developing technologies that do not fit within the three main categories of neutron detector technologies—proportional, scintillator, and semiconductor detectors.

efficiencies through methods such as creating three-dimensional surfaces to increase the amount of conversion material that can be applied to the chip. One such project is the DNDO-funded effort to develop semiconductors using boron-10 in 3-D pillar and trench structure. Other projects work to incorporate conversion material into the semiconductor material itself, such as the DNDO-supported program to develop boron triselenide (B_2Se_3) detectors.[29] While these projects often focus on developing ways to improve detection efficiencies, they also attempt to improve the fabrication techniques to produce new semiconductor detectors.

Proportional detectors, scintillators, and semiconductors are the major types of neutron detectors, but there are other, less common detector types. A few agency research and development projects are developing these other types of detectors. For example, a DOE-funded project is developing water-based neutron detectors—when conversion material, such as gadolinium, is in water, the water can be used as a neutron detector by observing the blue glow of Cherenkov radiation emitted when a neutron is absorbed by the conversion material.[30] Cherenkov radiation is light emitted when a charged particle passes through a medium at a speed greater than the velocity of light in that medium (see figure 4.1)—in this detector, the neutron absorption results in fast electrons that generate this Cherenkov radiation. According to NIST officials, the agency is supporting the development of a neutron detector that observes the ultraviolet light emitted by noble gas excimers—molecules in an excited electronic state—that form after boron-10 or lithium-6 absorbs a neutron in a noble gas, such as argon or xenon.

Figure 4.1 Cherenkov radiation illuminating reactor fuel assemblies immersed in water. Source: Photo courtesy of U.S. Department of Energy.

According to agency officials, after these technologies are explored in laboratory settings, they may become available for integration into neutron detector designs. They could then provide additional options for neutron detector designs and help to further reduce helium-3 demand.

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[29] B_2Se_3 is a new semiconductor material that can be used as an efficient neutron detector because boron-10 is a large fraction of its composition.

[30] In addition to boron-10 and lithium-6, gadolinium can be used as a conversion material. However, detectors using it have relatively poor gamma radiation discrimination.

5 Conclusions

Adopting alternative neutron detector technologies for research, security, and other applications is becoming increasingly important as the nation’s helium-3 supply continues to decrease. Since the helium-3 shortage was first realized in 2008, federal agencies have collaborated to mitigate its effects by identifying or developing alternative neutron detector technologies that do not use helium-3. Based on performance tests, three alternative detector technologies—boron-lined proportional detectors, boron trifluoride proportional detectors, and lithium-6 scintillators—appear to be potential replacement technologies for use in both large-area detectors and radiation portal monitors, although additional testing is under way.

Successful integration of alternative technologies in large-area detectors and successful testing of these detectors will allow science programs requiring additional large-area detectors to construct them using the alternative technologies, minimizing the impact of the helium-3 shortage on their research. We estimate one alternative detector technology—boron-10 lined proportional detectors—is at TRL 7 for use in radiation portal monitors, indicating such radiation portal monitors could be acquired and deployed with confidence that they will perform as required. Federal agencies should therefore be able to continue the deployment of radiation portal monitors with minimal additional program delays and with minimal use of additional helium-3. As these technologies are undergoing additional testing, federal agencies are funding the development of additional neutron detector technologies for security applications that may have broader application for research and industry and provide a greater range of neutron detector technologies to choose from.

6 External comments

6.1 Agency comments

We provided a draft of this report to the Secretaries of Commerce, Defense, Energy, and Homeland Security for their review and comment.

Neither Commerce nor DOD provided written comments. DOD provided technical comments that we incorporated as appropriate throughout the report.

DOE provided written comments, which are included in section 7.6 . DOE generally agreed with the report but noted that BF_3 is a proven, inexpensive, and reliable alternative with minimal development cost, that detectors containing BF_3 use small quantities of the gas, which mitigates the impacts of leaks from such detectors, and that the Department of Transportation does not consider less than 1 gram of BF_3 in portable instruments hazardous. We agree with these statements but note that while BF_3 has been successfully used in other applications, detectors using BF_3 must still undergo testing for the specific applications explored in this report to verify they can satisfy all applicable requirements in their expected operational environments. Furthermore, the hazardous nature of BF_3—and the ways in which its effects can be mitigated—will still need to be considered by agencies selecting a detector. DOE also noted the instruments at SNS will be less efficient if they use an alternative to helium-3. We have modified the report to reflect that while alternative technologies may be viable for some large-area detectors, others may be planned for with requirements for very high neutron detection efficiency that may only be satisfied by using helium-3. Such high performance detectors will require a decision based on the cost-benefit analysis of using the limited supply of helium-3 or accepting the lower performance provided by an alternative technology. DOE provided technical comments that we incorporated as appropriate throughout the report.

DHS provided written comments, which are included in section 7.7. In its comments, DHS further highlighted the role of its DNDO in addressing the helium-3 shortage and its interaction with the interagency policy committee that was formed to address the shortage. DHS provided technical comments that we incorporated as appropriate throughout the report.

6.2 Expert comments

We provided a draft of this report to our group of external experts for their review and comment—all eight responded (see section 7.1 for a description of this group's contributions and section 7.5 for a list of the experts). The majority of them expressed general agreement with the draft, and none expressed disagreement. One reviewer expressed concern about the drafts balance between short- and long-term neutron detector solutions. We note that this report focuses on alternative technologies currently available because they could provide the most immediate reduction in demand for helium-3. The eight respondents also provided technical comments that we incorporated as appropriate throughout the report.

7 Appendices

7.1 Objectives, scope, and methodology

In this report, our objectives were to assess (1) what alternative neutron detectors are currently available and their effectiveness and (2) the status of alternative neutron detector technologies that are being researched for future availability. To address these objectives, we reviewed program documents from the various agencies, including test results for all the currently available alternatives, contract information, and proposals; product information from vendors; and scientific literature. We also attended two symposiums on alternative neutron detectors, including the 2010 Institute of Electrical and Electronics Engineers Nuclear Science Symposium, Medical Imaging Conference, and 17th International Workshop on Room-Temperature Semiconductor X-ray and Gamma-ray Detectors in Knoxville, Tennessee, and the 2010 Symposium on Radiation Measurements and Application at the University of Michigan in Ann Arbor. We also visited the neutron detector test facilities at the Department of Energy's (DOE) Pacific Northwest National Laboratory (PNNL), as well as DOE's Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (ORNL), which relies on helium-3 in large-area detectors for conducting scientific research.

With the assistance of the National Academy of Sciences (NAS), we identified a group of eight experts from academia and federally funded research and development centers who had relevant expertise and knowledge in one or more of the following areas: (1) technology development, particularly with respect to neutron detectors; (2) nuclear physics and nuclear engineering; (3) neutron detector applications, including for security, science, and medicine. They helped us identify alternative neutron detector technologies currently available or being developed for future use in research and security applications. This group of experts also reviewed and commented on a draft of this report.

For the first objective, we limited our assessment to alternative detectors for large-area detectors for science applications and for security applications, specifically radiation portal monitors. These two applications create the greatest demand for helium-3, and alternative detector technologies for these applications would therefore have the greatest impact on alleviating helium-3 demand. We further restricted our review to technologies that are "currently available"—those that are already commercially available in other neutron detection applications and available for integration into large-area detectors or radiation portal monitors. Accordingly, we reviewed information from and interviewed officials at the two U.S. facilities participating in an international collaboration of facilities using large-area detectors—the Department of Commerce's National Institute for Standards and Technology (NIST) and DOE's ORNL. We interviewed officials at NIST and ORNL who worked with the international collaboration of large science facilities that are examining alternative technologies. We limited our discussions with members of this working group to U.S. members because of their knowledge of how U.S. facilities would be affected. We reviewed the international collaboration's plans for developing and testing detectors using alternative technologies, which included guideline criteria for detectors.

To determine what alternative neutron detectors are currently available for integration into deployable products for security applications, we interviewed and received documentation from officials in Commerce, DOD, DOE, and DHS; and officials from the national laboratories conducting work in this area: PNNL, ORNL, Los Alamos National Laboratory (LANL), and Sandia National Laboratories (SNL). To determine the criteria for the effectiveness of neutron detectors used for radiation portal monitors, we reviewed the relevant American National Standards Institute (ANSI) standards and the PNNL-developed radiation portal monitor requirements used for procuring DHS's radiation portal monitors.

To determine the relative gamma radiation discrimination and neutron detection efficiency capabilities of the neutron-detecting isotopes helium-3, boron-10, and lithium-6, for each isotope we obtained the energy released by the neutron-absorbing reactions and the cross-section of those reactions from the scientific literature. We used these values to compare the capabilities of these isotopes. To determine the performance characteristics of potential alternative detector technologies, such as their detection efficiencies or gamma radiation discrimination capabilities, we reviewed relevant research and testing documentation from PNNL and ORNL on each potential technology we identified. We also interviewed detector developers and manufacturers producing the three technologies we identified in the first objective. We determined whether the alternative technologies have demonstrated capabilities that met or exceeded the primary performance requirements of neutron detection efficiency and gamma radiation discrimination.

To estimate the technology readiness levels (TRL) of radiation portal monitors using potential alternative detector technologies, we reviewed relevant research and testing documentation from DHS and the national laboratories on each technology that we identified in the first objective. We estimated the TRL of each currently available technology based on this research and testing documentation by determining, for each technology, the type of prototype that was tested (for example, whether it was a relatively immature laboratory system or a more mature production model), the testing that was performed (for example, whether it involved laboratory simulations of environments or field testing in operational environments), and the results of this testing, using the DHS radiation portal monitor requirements as a metric. We then compared each technology's prototype and testing status to the NASA TRL scale. We used this scale because it is the basis for other TRL scales, such as DOD's TRL calculator. Furthermore, according to DNDO officials, DNDO typically uses the NASA TRL scale when it performs TRL assessments. Because multiple vendors have developed multiple designs using these alternative technologies, the TRL we estimate for each technology is the highest TRL we estimate for a design using that technology. We discussed our TRL estimates with DNDO officials, who generally concurred with our estimates based on our application of the NASA TRL scale, but who also noted that these technologies have been successfully used for other neutron detector applications and might have higher TRLs when considered for these other applications.

For the second objective, we assessed technologies that are not readily available for any application, but are under development. We focused on technologies funded by Commerce, DHS, DOD, and DOE. The interagency policy committee addressing the helium-3 shortage identified these Departments' programs as part of the committee's work to mitigate demand for helium-3. To determine the status of alternative detector technologies being researched for future use, we interviewed and requested information from officials from Commerce, DHS, DOD, and DOE, and the national laboratories conducting work in this area—LANL, ORNL, PNNL, and SNL. We reviewed program documentation on alternative technologies, including contract information, technical proposals, scientific literature, and program updates.

We conducted our work from July 2010 to September 2011 in accordance with all sections of GAO's quality assurance framework that are relevant to technology assessments. The framework requires that we plan and perform the engagement to obtain sufficient and appropriate evidence to meet our stated objectives and to discuss any limitations to our work. We believe that the information and data obtained, and the analysis conducted, provide a reasonable basis for any findings and conclusions in this product.

7.2 Boron and lithium isotopes are alternatives to helium-3

The three main categories of neutron detectors—proportional, scintillator, and semiconductor—can use isotopes other than helium-3 as conversion material to absorb and detect neutrons. Boron-10 and lithium-6 are the most common alternative isotopes to helium-3 for use in neutron detectors.[31] These isotopes can be chemically combined with other elements to create molecules that also act as conversion materials. For example, boron-10 and fluorine can be used to create boron trifluoride gas, which can be used in sealed tubes in much the same way as helium-3 has been used in proportional detectors. DHS considers both boron-10 and lithium-6 to be in sufficient supply for neutron detectors needed for future radiation portal monitor deployments. Furthermore, according to DOE officials, the U.S. stockpile of lithium-6 is sufficient to meet neutron detector demand. Both boron-10 and lithium-6 are export-controlled materials, meaning that licenses are required when exporting boron or lithium enriched in these isotopes to certain countries.

The suitability of a detector for an application derives from both the characteristics of the isotope and the detector's design. Factors such as how a neutron absorbing isotope is integrated into the conversion material, the arrangement of the moderator relative to the conversion material, and the signal processing for the detector influence the detector's characteristics. For example, while lithium-6 can have excellent gamma radiation discrimination, when it is used in a scintillator, the resulting detector must use good signal processing techniques to achieve good gamma radiation discrimination because scintillator materials are generally sensitive to gamma radiation. Table 7.1 compares the performance characteristics of the two alternative isotopes, with helium-3 included for comparison, and the categories of detectors in which they are typically used.

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[31] Other materials can be used for conversion materials, but are less common due to significant weaknesses. For example, gadolinium can be used, but it has poor gamma radiation discrimination. Fissile nuclear material can also be used, but such detectors typically have low efficiencies and can require safeguards to secure the detector itself.

Isotope	Potential gamma radiation discrimination[a]	Potential neutron detection efficiency[b]	Typical detector type
Helium-3 (for comparison)	Good (0.76 MeV)	Excellent (5,333 barns)	Proportional
Boron-10	Very good (2.3 MeV)	Very Good (3,835 barns)	Proportional, scintillator, or semiconductor
Lithium-6	Excellent (4.78 MeV)	Good (940 barns)	Scintillator or semiconductor

Table 7.1 Three isotopes commonly used as conversion materials in neutron detectors. Source: GAO analysis based on agency documents and physical properties of these isotopes.

[a] Qualitative assessments of the energies of the neutron absorption reaction products (which are fast-moving charged particles), with energies measured in mega-electronvolts (MeV) and indicated in parentheses in this column. The qualitative assessments are based on the energy released by a neutron interaction, but without consideration of additional factors such as the specifics of a particular detector design. The higher the product energy, the more energy that the detector can use to determine if a neutron is detected; thus, higher-energy products can prove beneficial in determining that a signal is not due to a low-energy source of radiation, such as a gamma radiation source. We define "good" at 0.5 to 2 MeV; "very good", 2 to 4 MeV; and "excellent", greater than 4 MeV.

[b] Qualitative assessments of the thermal neutron reaction cross-section, which is a measure of how likely an incoming neutron will be absorbed by a conversion material atom. The cross-section is measured in barns, where one barn is 10^{-28} square meters, and is indicated in parentheses in this column. The higher the cross-section, the more likely an absorption reaction can occur for an incoming neutron, which is beneficial when considering a detector's efficiency at detecting neutrons. We define "good" at 500 to 2000 barns; "very good", 2000 to 4000 barns; and "excellent", greater than 4000 barns.

7.3 Requirements for alternative neutron detectors for use in large-area detectors and radiation portal monitors

Neutron detectors have several characteristics that are important in judging performance for particular applications, including large-area detectors and radiation portal monitors. These include:

- *Neutron detection efficiency,* used for both large-area detectors and radiation portal monitors, specifies how well a neutron detector should detect neutrons. It can be defined in different ways—for example, for a specified detector size and shape, and with a specified type of neutron source, the absolute neutron detection efficiency describes the number of neutrons a detector will count per second. Neutron detection efficiency can also be defined as the likelihood that any particular neutron passing through a detector will be detected (as opposed to not being detected at all)—this is the intrinsic neutron detection efficiency. Large-area detectors need higher neutron detection efficiencies, while neutron detectors used in radiation portal monitors can be effective with lower neutron detection efficiencies.

- *Gamma radiation discrimination* (or gamma radiation rejection) specifies the maximum fraction of incident gamma rays that a detector can falsely identify as neutrons. Both large-area detectors and radiation portal monitors use a requirement that the gamma radiation discrimination be less than 10^{-6}, which indicates that less than one in a million gammas can result in a false positive neutron detection.

- *Gamma absolute rejection ratio for neutrons* (GARRn), used for radiation portal monitors, specifies the neutron detector response in the presence of both neutrons and gamma radiation. It is the ratio of the absolute neutron detector efficiency (defined above), as measured with simultaneous neutron and gamma radiation sources, to the absolute neutron detection efficiency, as measured with only a neutron source. A GARRn of 1.0 would indicate these two measurements are the same and, therefore, that the gamma radiation source had no effect on the neutron detection efficiency of the detector.

- *Detector size and spatial resolution* establish physical requirements for the detectors. Large-area detectors must have larger surface areas, while neutron detectors for radiation portal monitors must fit within a specified volume. Large-area detectors must have spatial resolution, which is the capability of a detector to determine where on a detector a neutron is detected.

- *Time resolution,* used for large-area detectors, specifies how well a detector must determine when neutrons are detected. Large-area detectors must have a time resolution of a microsecond (one millionth of a second).

- *Environmental requirements* determine what conditions a detector must operate under. For example, large-area detectors may be used at ultra-low temperatures or in vacuum. Radiation portal monitors are deployed outdoors in potentially harsh conditions, requiring operation in environments with high humidity, rain, ice, dust and sand, and seasonal temperature variations.

7.4 Technology readiness levels

Technology readiness levels (TRLs) are commonly used to assess the maturity of a technology for a specific application. They range from TRL 1 to TRL 9, and the levels, as defined by the National Aeronautics and Space Administration (NASA), are described in table 7.2. Terminology used with TRLs is described after table 7.2.

Technology readiness level	Description	Hardware/ software	Demonstration environment
1. Basic principles observed and reported	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Examples might include paper studies of a technology's basic properties.	None (paper studies and analysis)	None
2. Technology concept and/ or application formulated	Invention begins. Once basic principles are observed, practical applications can be invented. The application is speculative and there is no proof or detailed analysis to support the assumption. Examples are still limited to paper studies.	None (paper studies and analysis)	None
3. Analytical and experimental critical function and/or characteristic proof of concept	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.	Analytical studies and demonstration of nonscale individual components (pieces of subsystem)	Lab
4. Component and/or breadboard validation in laboratory environment	Basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared to the eventual system. Examples include integration of "ad hoc" hardware in a laboratory.	Low-fidelity breadboard. Integration of nonscale components to show pieces will work together. Not fully functional or form or fit but representative of technically feasible approach suitable for flight articles.	Lab

Technology readiness level	Description	Hardware/ software	Demonstration environment
5. Component and/or breadboard validation in relevant environment	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so that the technology can be tested in a simulated environment. Examples include “high fidelity” laboratory integration of components.	High-fidelity breadboard. Functionally equivalent but not necessarily form and/ or fit (size weight, materials, etc). Should be approaching appropriate scale. May include integration of several components with reasonably realistic support elements/subsystems to demonstrate functionality.	Lab demonstrating functionality but not form and fit. May include flight demonstrating breadboard in surrogate aircraft. Technology ready for detailed design studies.
6. System/ subsystem model or prototype demonstration in a relevant environment	Representative model or prototype system, which is well beyond the breadboard tested for TRL 5, is tested in a relevant environment. Represents a major step up in a technology’s demonstrated readiness. Examples include testing a prototype in a high fidelity laboratory environment or in simulated realistic environment.	Prototype. Should be very close to form, fit and function. Probably includes the integration of many new components and realistic supporting elements/ subsystems if needed to demonstrate full functionality of the subsystem.	High-fidelity lab demonstration or limited/ restricted flight demonstration for a relevant environment. Integration of technology is well defined.
7. System prototype demonstration in a realistic environment	Prototype near or at planned operational system. Represents a major step up from TRL 6, requiring the demonstration of an actual system prototype in a realistic environment, such as in an aircraft, vehicle or space. Examples include testing the prototype in a test bed aircraft.	Prototype. Should be form, fit and function integrated with other key supporting elements/subsystems to demonstrate full functionality of subsystem.	Flight demonstration in representative realistic environment such as flying test bed or demonstrator aircraft. Technology is well substantiated with test data.

Technology readiness level	Description	Hardware/ software	Demonstration environment
8. Actual system completed and "flight qualified" through test and demonstration	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications.	Flight-qualified hardware	Developmental Test and Evaluation (DT&E) in the actual system application.
9. Actual system "flight proven" through successful mission operations	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. In almost all cases, this is the end of the last "bug fixing" aspects of true system development. Examples include using the system under operational mission conditions.	Actual system in final form	Operational Test and Evaluation (OT&E) in operational mission conditions.

Table 7.2 TRLs as defined by NASA. Source: GAO and its analysis of National Aeronautics and Space Administration data.

Proof of Concept: Analytical and experimental demonstration of hardware/software concepts that may or may not be incorporated into subsequent development and/or operational units.

Breadboard: A low fidelity unit that demonstrates function only, without respect to form or fit in the case of hardware, or platform in the case of software. It often uses commercial and/or ad hoc components and is not intended to provide definitive information regarding operational performance.

Brassboard: A medium fidelity functional unit that typically tries to make use of as much operational hardware/software as possible and begins to address scaling issues associated with the operational system. It does not have the engineering pedigree in all aspects, but is structured to be able to operate in simulated operational environments in order to assess performance of critical functions.

Prototype Unit: The prototype unit demonstrates form, fit, and function at a scale deemed to be representative of the final product operating in its operational environment. A subscale test article provides fidelity sufficient to permit validation of analytical models capable of predicting the behavior of full-scale systems in an operational environment.

Engineering Unit: A high fidelity unit that demonstrates critical aspects of the engineering processes involved in the development of the operational unit. Engineering test units are intended to closely resemble the final product (hardware/software) to the maximum extent possible and are built and tested so as to establish confidence that the design will function in the expected environments. In some cases, the engineering unit will become the final product, assuming proper traceability has been exercised over the components and hardware handling.

Mission Configuration: The final architecture/system design of the product that will be used in the operational environment. If the product is a subsystem/component, then it is embedded in the actual system in the actual configuration used in operation.

Laboratory Environment: An environment that does not address in any manner the environment to be encountered by the system, subsystem, or component (hardware or software) during its intended operation. Tests in a laboratory environment are solely for the purpose of demonstrating the underlying principles of technical performance (functions), without respect to the impact of environment.

Relevant Environment: Not all systems, subsystems, and/or components need to be operated in the operational environment in order to satisfactorily address performance margin requirements. Consequently, the relevant environment is the specific subset of the operational environment that is required to demonstrate critical "at risk" aspects of the final product performance in an operational environment. It is an environment that focuses specifically on "stressing" the technology advance in question.

Operational Environment: The environment in which the final product will be operated. In the case of space flight hardware/software, it is space. In the case of ground-based or airborne systems that are not directed toward space flight, it will be the environments defined by the scope of operations. For software, the environment will be defined by the operational platform.

7.5 Expert participation in the engagement

At our request, the following individuals helped us to identify currently available alternative neutron detector technologies and those under development. They also reviewed and provided comments on the draft of this report:

Yacouba Diawara, Oak Ridge National Laboratory, Oak Ridge, Tennessee

Glenn F. Knoll, University of Michigan, Ann Arbor, Michigan

Richard T. Kouzes, Pacific Northwest National Laboratory, Richland, Washington

Craig Marianno, Texas A&M University, College Station, Texas

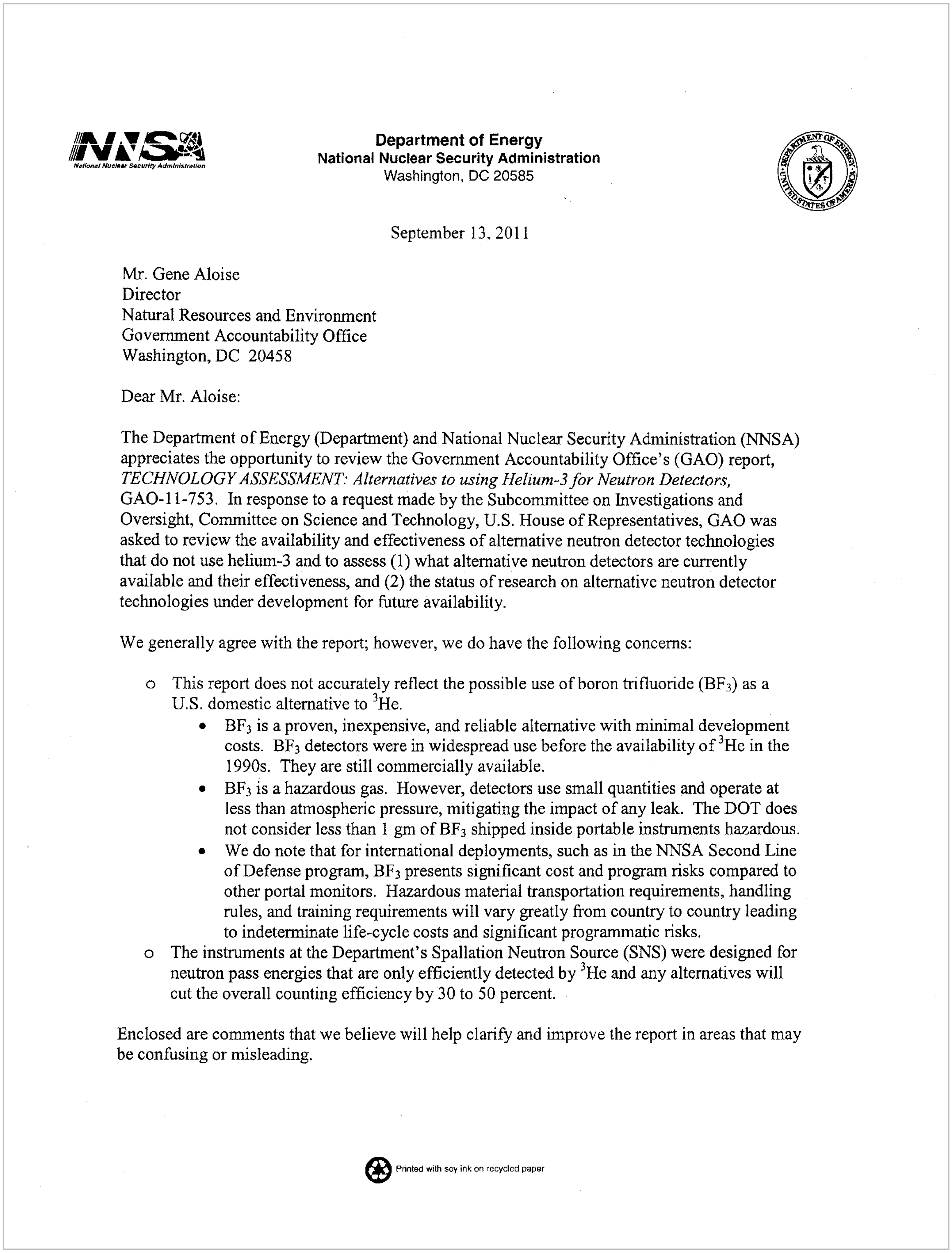
Keith Marlow, Sandia National Laboratories, Albuquerque, New Mexico

Stanley G. Prussin, University of California, Berkeley, California

Tor Raubenheimer, Stanford Linear Accelerator Center, Menlo Park, California

George Thompson, Homeland Security Studies & Analysis Institute, Arlington, Virginia

7.6 Comments from the Department of Energy



Department of Energy
National Nuclear Security Administration
Washington, DC 20585

September 13, 2011

Mr. Gene Aloise
Director
Natural Resources and Environment
Government Accountability Office
Washington, DC 20458

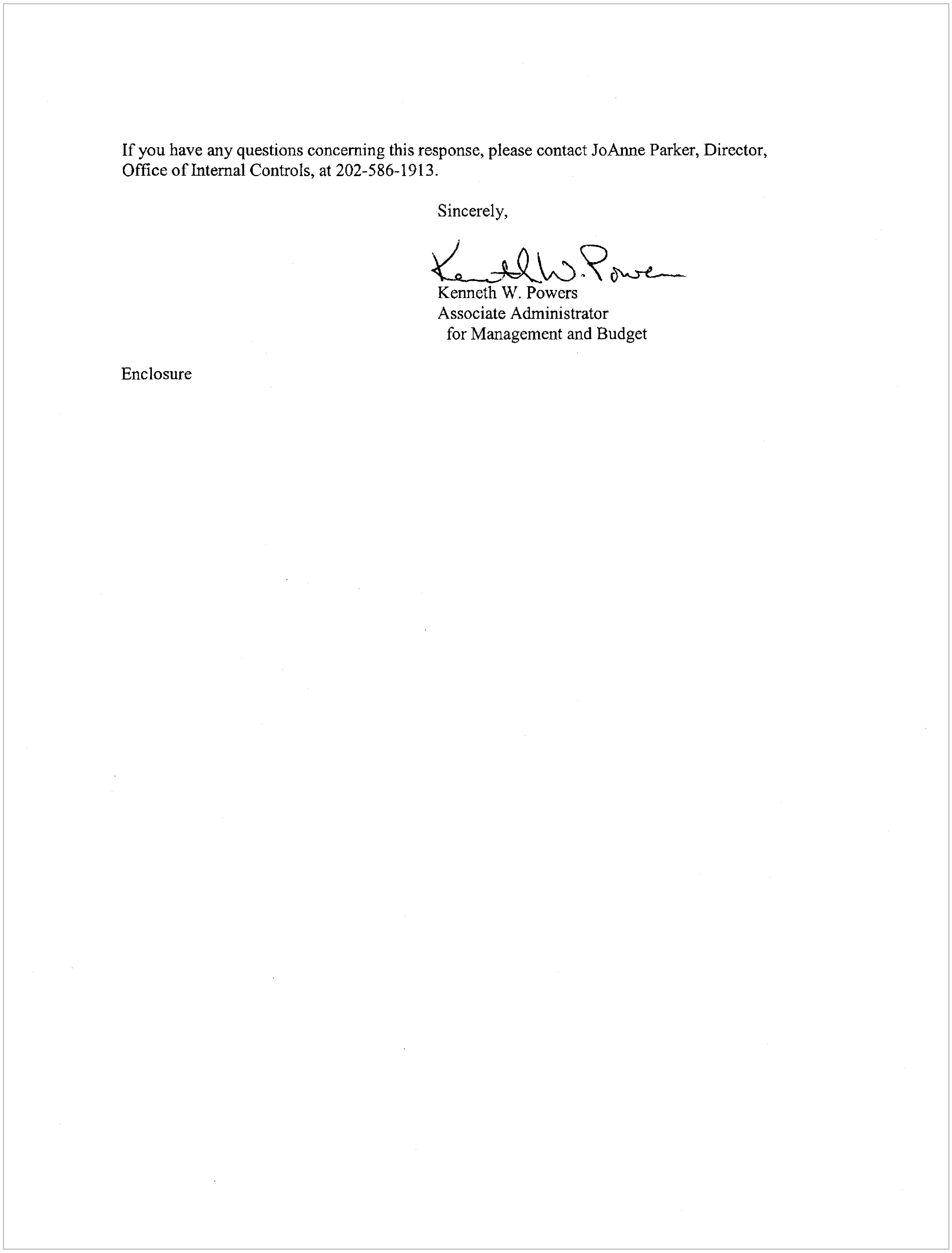
Dear Mr. Aloise:

The Department of Energy (Department) and National Nuclear Security Administration (NNSA) appreciates the opportunity to review the Government Accountability Office's (GAO) report, *TECHNOLOGY ASSESSMENT: Alternatives to using Helium-3 for Neutron Detectors,* GAO-11-753. In response to a request made by the Subcommittee on Investigations and Oversight, Committee on Science and Technology, U.S. House of Representatives, GAO was asked to review the availability and effectiveness of alternative neutron detector technologies that do not use helium-3 and to assess (1) what alternative neutron detectors are currently available and their effectiveness, and (2) the status of research on alternative neutron detector technologies under development for future availability.

We generally agree with the report; however, we do have the following concerns:

- This report does not accurately reflect the possible use of boron trifluoride (BF_3) as a U.S. domestic alternative to ^3He.
    - BF_3 is a proven, inexpensive, and reliable alternative with minimal development costs. BF_3 detectors were in widespread use before the availability of ^3He in the 1990s. They are still commercially available.
    - BF_3 is a hazardous gas. However, detectors use small quantities and operate at less than atmospheric pressure, mitigating the impact of any leak. The DOT does not consider less than 1 gm of BF_3 shipped inside portable instruments hazardous.
    - We do note that for international deployments, such as in the NNSA Second Line of Defense program, BF_3 presents significant cost and program risks compared to other portal monitors. Hazardous material transportation requirements, handling rules, and training requirements will vary greatly from country to country leading to indeterminate life-cycle costs and significant programmatic risks.
- The instruments at the Department's Spallation Neutron Source (SNS) were designed for neutron pass energies that are only efficiently detected by ^3He and any alternatives will cut the overall counting efficiency by 30 to 50 percent.

Enclosed are comments that we believe will help clarify and improve the report in areas that may be confusing or misleading.



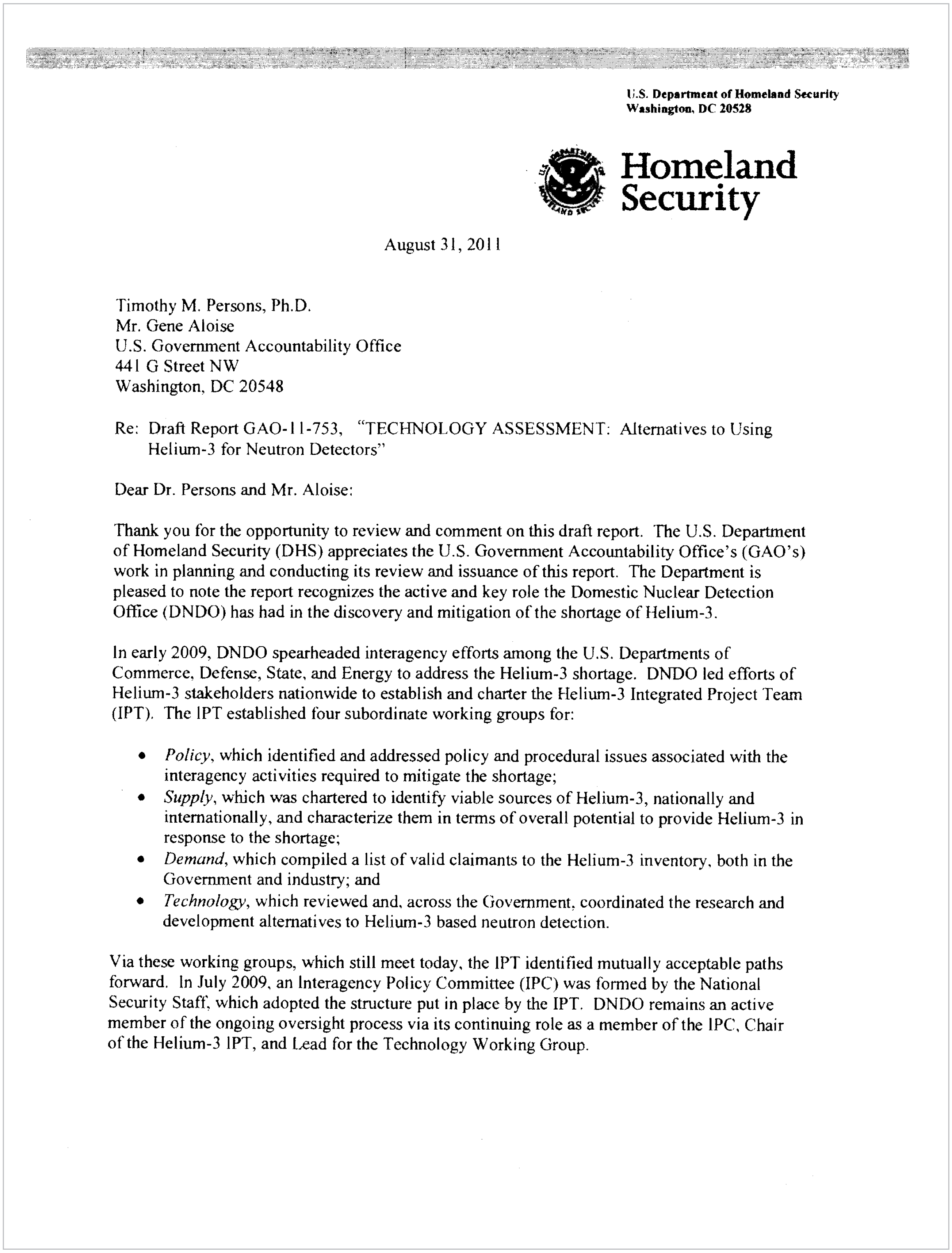
If you have any questions concerning this response, please contact JoAnne Parker, Director, Office of Internal Controls, at 202-586-1913.

Sincerely,

Kenneth W. Powers
Associate Administrator
for Management and Budget

Enclosure

7.7 Comments from the Department of Homeland Security



U.S. Department of Homeland Security
Washington, DC 20528

Homeland
Security

August 31, 2011

Timothy M. Persons, Ph.D.
Mr. Gene Aloise
U.S. Government Accountability Office
441 G Street NW
Washington, DC 20548

Re: Draft Report GAO-11-753, "TECHNOLOGY ASSESSMENT: Alternatives to Using Helium-3 for Neutron Detectors"

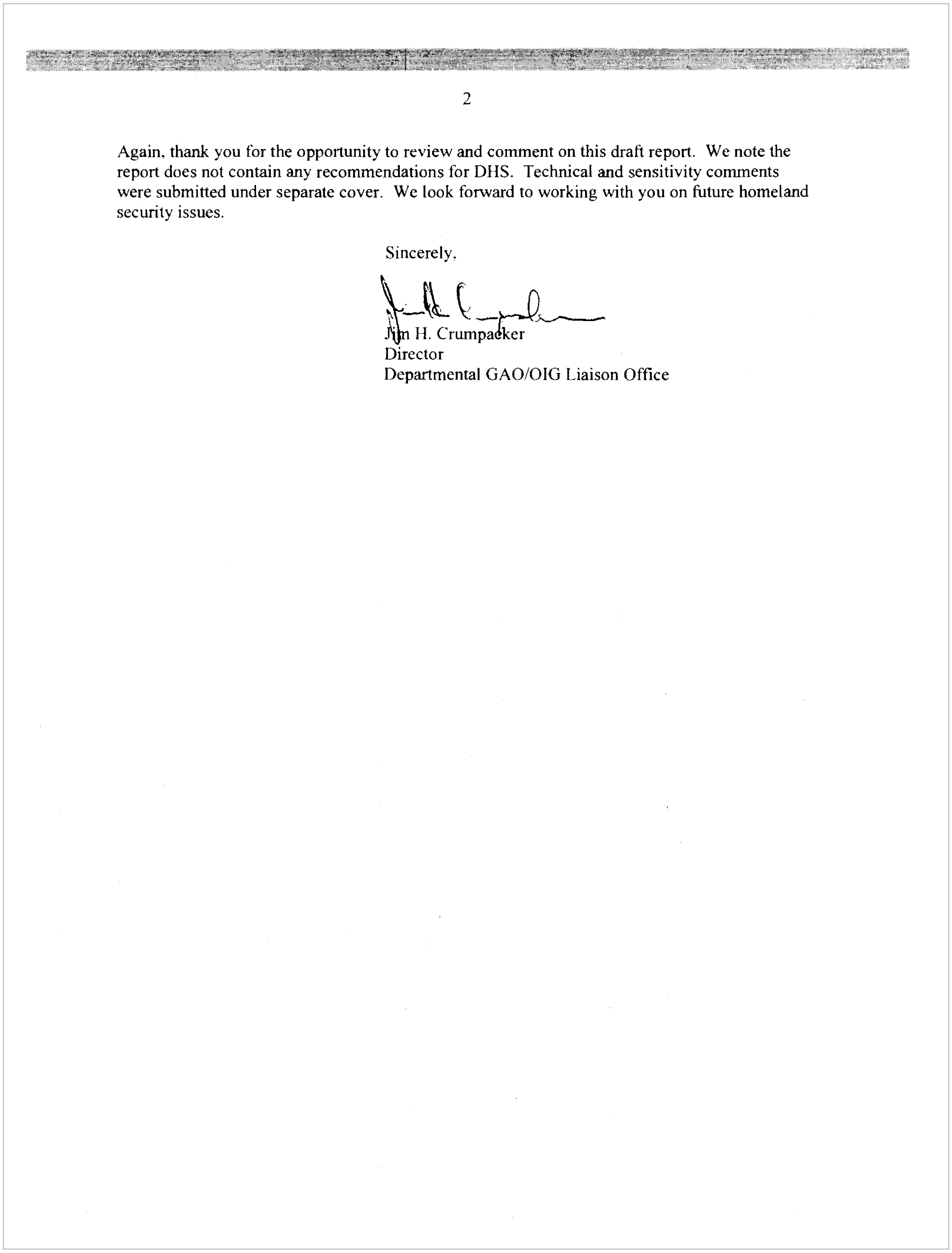
Dear Dr. Persons and Mr. Aloise:

Thank you for the opportunity to review and comment on this draft report. The U.S. Department of Homeland Security (DHS) appreciates the U.S. Government Accountability Office's (GAO's) work in planning and conducting its review and issuance of this report. The Department is pleased to note the report recognizes the active and key role the Domestic Nuclear Detection Office (DNDO) has had in the discovery and mitigation of the shortage of Helium-3.

In early 2009, DNDO spearheaded interagency efforts among the U.S. Departments of Commerce, Defense, State, and Energy to address the Helium-3 shortage. DNDO led efforts of Helium-3 stakeholders nationwide to establish and charter the Helium-3 Integrated Project Team (IPT). The IPT established four subordinate working groups for:

- *Policy*, which identified and addressed policy and procedural issues associated with the interagency activities required to mitigate the shortage;
- *Supply*, which was chartered to identify viable sources of Helium-3, nationally and internationally, and characterize them in terms of overall potential to provide Helium-3 in response to the shortage;
- *Demand*, which compiled a list of valid claimants to the Helium-3 inventory, both in the Government and industry; and
- *Technology*, which reviewed and, across the Government, coordinated the research and development alternatives to Helium-3 based neutron detection.

Via these working groups, which still meet today, the IPT identified mutually acceptable paths forward. In July 2009, an Interagency Policy Committee (IPC) was formed by the National Security Staff, which adopted the structure put in place by the IPT. DNDO remains an active member of the ongoing oversight process via its continuing role as a member of the IPC, Chair of the Helium-3 IPT, and Lead for the Technology Working Group.



Again, thank you for the opportunity to review and comment on this draft report. We note the report does not contain any recommendations for DHS. Technical and sensitivity comments were submitted under separate cover. We look forward to working with you on future homeland security issues.

Sincerely,

Jim H. Crumpacker
Director
Departmental GAO/OIG Liaison Office

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GAO contacts and staff acknowledgements

GAO contacts

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Gene Aloise, (202) 512-3841 or aloisee@gao.gov

Staff acknowledgments

In addition to the persons named above, **Ned H. Woodward,** Assistant Director; R. **Scott Fletcher;** and **Wyatt R. Hundrup** made key contributions. **Pille Anvelt, Kendall Childers, Cindy Gilbert, Rich Hung, Mehrzad Nadji, Penny Pickett, and Kim Raheb** also made important contributions.

Other GAO technology assessments

TECHNOLOGY ASSESSMENT: Climate Engineering: Technical status, future directions, and potential responses. GAO-11-71. Washington, D.C.: July 28, 2011.

TECHNOLOGY ASSESSMENT: Explosives Detection Technology to Protect Passenger Rail. GAO-10-898. Washington, D.C.: July 28, 2010.

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