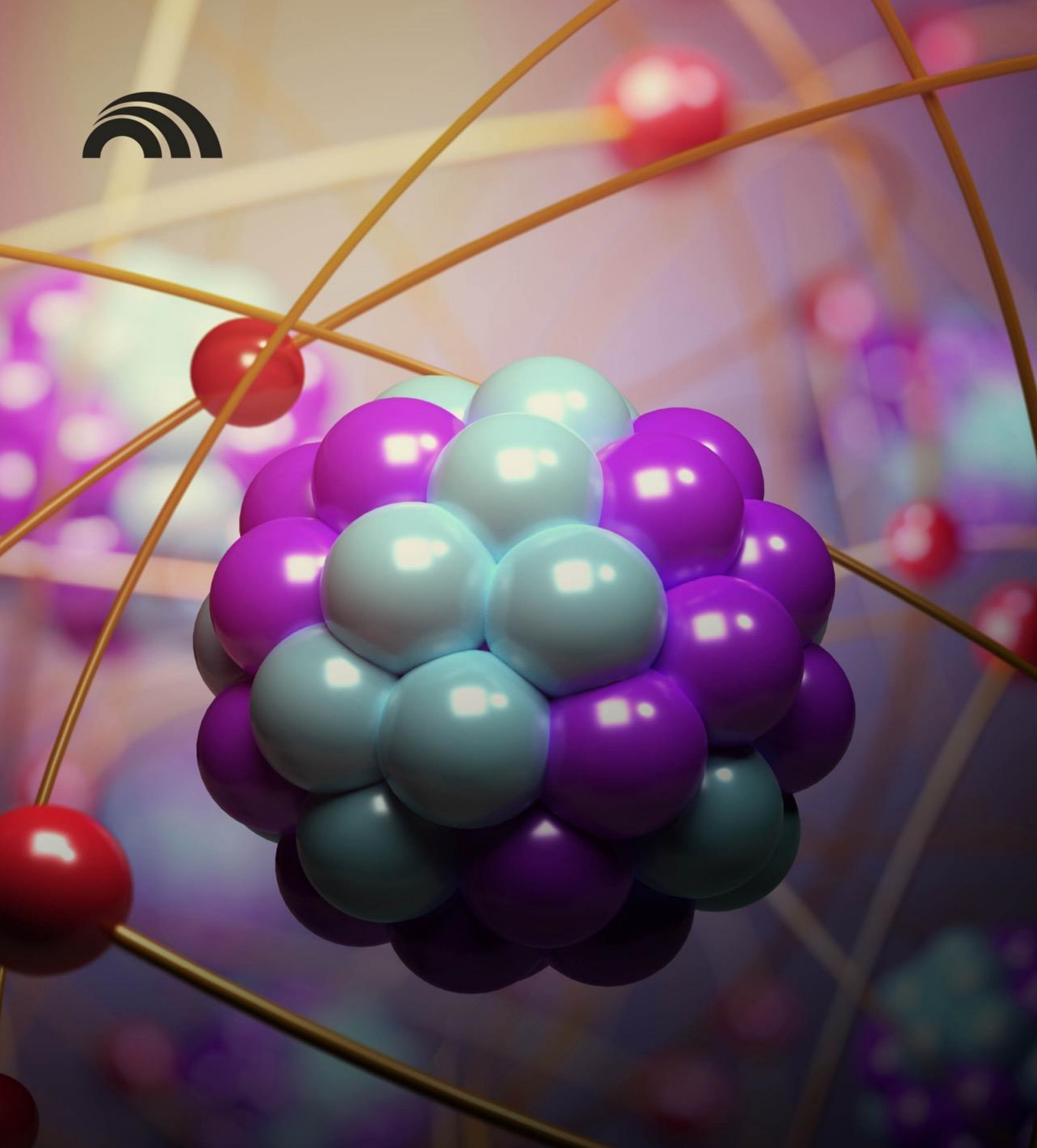

DOE | NUCLEAR PHYSICS INSTRUMENTATION, DETECTION SYSTEMS & TECHNIQUES

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Prepared by Dawnbreaker® • 2117 Buffalo Road • Rochester, NY • 14624 • (585) 594-0025 • www. dawnbreaker.com

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1.0 Introduction

The Department of Energy's (DOE) Office of Nuclear Physics (NP) supports research on state-of-the-art scientific instrumentation to advance nuclear physics research, not only at NP user facilities, but also at other research institutions world-wide. This report is intended to support that goal by identifying (1) NP-specific projects that could be of interest/use to other institutions including other federal agencies and academic institutions and (2) identifying programs within organizations that appear to have synergies with various NP-funded projects. This report addresses four research areas identified in a recent Funding Opportunity Announcement (FOA) for the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs:

1. **Advances in Detector and Spectrometer Technology including Novel Gas and Solid-State Detectors**
2. **Technology for Rare Decay and Rare Particle Detection**
3. **High Performance Scintillators, Cherenkov Materials and Other Optical Components**
4. **Technology for High Radiation Environments**

1.1. Methodology

The purpose of the market research is to provide insight into organizations and applications that could benefit from advances in nuclear physics. An emphasis is placed on information regarding other federal agencies, as they could be potential sources of additional SBIR/STTR funding to expand the use of the technology platform and/or a source of potential Phase III funding.

Brief sections are also included on the size of the larger market opportunity using a variety of subscription databases (MarketsandMarkets, BCC Research and Frost & Sullivan).

2.0 Advances in Detector and Spectrometer Technology Including Novel Gas and Solid-state Detectors

To advance nuclear physics research there is a need for devices to detect, analyze, and track photons, charged particles, and neutral particles such as neutrons, neutrinos, and single atoms. Specific advances in detectors that are sought include:

- Low-cost large area Multi-channel Plate (MCP) type detector with high
- Spatial resolution (≤ mm2), high-rate capability (≥200 kHz/cm2)
- Large area Multigap Resistive Plate Chamber (MRPC) detectors with very high-rate capability, radiation and magnetic field tolerance and high timing resolution, with the same specs as above for time-of-flight detectors.
- Cherenkov detectors
- Large area electromagnetic calorimetry with high energy and spatial resolution.

Particle identification using machine learning techniques such as:

- Algorithms for event classification, track recognition and particle identification
- Particle Flow algorithms to enhance hadron calorimetry
- Event identification for low background detectors, such as those used in neutrinoless double beta decay.

Advances in Novel Gas and Solid-State Detectors

- Heavy ion focal plane detectors or detector systems for magnetic spectrometers and recoil separators including associated readout electronic and data acquisition systems
- Novel detector concepts such as Micropattern Gas Detectors (GEMs, Micromegas, MicroRWELLs, etc.) and Parallel Plate Avalanche Chambers, for charged particle tracking
- New charged particle detectors for particle identification-based energy loss measurement, with energy resolution (< 1% at 1 MeV)
- High-rate, high-radiation hard, precision tracking devices
- Large area monocrystalline diamond detectors of uniform thickness and strip or pixelated readout
- Readout for the above with high-speed data buffering compatible.

2.1. Potential Applications

Gamma and neutron detectors are broadly used for defense and homeland security applications involving detection, tracking, and utilization of nuclear materials. As an example of need, the interagency "Nuclear Defense Research and Development Strategic Plan for Fiscal Years 2020-2024" report identifies the following technologies for quick N/R detection to fulfill future needs,

> "Improved detection capabilities for both neutrons and gamma-rays, particularly for special nuclear material, to include unmanned and autonomous systems capable of searching large areas quickly in remote, urban, and limited access environments. These technologies should be capable of determining direction to source material using networked or non-networked systems with a focus on enabling wide-area search and monitoring and radiation mapping capability development. Work should also investigate tri-mode materials that enable thermal and fast neutron detection plus spectroscopic gamma. Research should also identify new spectroscopic plastic scintillators capable of drop-in replacement in legacy deployed portal monitors."[1]

Detectors with improved performance in the areas identified will also advance research in other application areas including medical imaging, photonics, high energy physics, power plant inspection, incident management and monitoring applications. Such detectors could also be employed in particle collider experiments, neutrinoless double-beta decay experiments, neutrino experiments.[2]

Interest in radiation detection, monitoring, and safety cuts across many agencies, including the Department of Defense (DoD), Department of Homeland Security (DHS), National Aeronautics and Space Administration (NASA), as well as the Departments of Health and Human Services (HHS), Department of Energy (DOE), and Department of Justice. These agencies fund research on radiation/nuclear detection technologies and may be appropriate to consider as Phase III partners. The activities and synergistic programs within the agencies listed above are further discussed in the rest of this report. Groups within DOE are excluded from this report since the main objective is to identify other potential sources of Phase III funding.

2.2. Department of Defense

The Department of Defense (DoD) presents several potential transition opportunities for detector technologies. DoD has a long history in radiological and nuclear detection in support of military-specific missions. Making inroads within the DoD depends heavily on identifying and pursuing those programs and program offices that have an expressed need and the funding for such a technology.

2.2.1. *Defense Threat Reduction Agency*

The Defense Threat Reduction Agency (DTRA) is DoD's principal Research, Development, Test & Evaluation (RDT&E) program for combating and countering weapons of mass destruction (WMD). Detecting, deterring and defeating these threats is a DoD priority, and DTRA's mission.[3] As part of its mission the DTRA monitors U-235, U-233, Pu-239U, and Cs-137, which are used in nuclear weapons and dirty bombs. These materials emit gammas and neutrons spontaneously and when excited by bremsstrahlung (photo-fusion) and hence are key indicators of the presence of such material. Although DTRA has much broader interests, the detection and monitoring of these isotopes is a key driver in the development and deployment of gamma and neutron detectors.

DTRA is organized into seven mission directorates: Cooperative Threat Reduction Directorate, Research and Development Directorate, Operations and Integration Directorate, On-Site Inspection and Building Capacity Directorate, Nuclear Enterprise Directorate, Information Management and Technology Directorate, Strategic Integration Directorate, and its supporting Staff Offices.[4] DTRA's Headquarters is located at Fort Belvoir, Virginia.[5]

The research and development portfolio span the technology spectrum from basic through applied research and, often includes the capability to test new advanced technology capabilities. DTRA conducts network analysis to identify critical links and nodes between people, places, and things. DTRA maintains global situational awareness of countering WMD and improvised threat networks and facilitates information sharing across communities of action.[6]

DTRA is focused specifically on meeting DoD R&D needs for radiation/nuclear detection and has been involved in R&D pertaining to detectors and detector materials.[7]

- DTRA's Chemical and Biological Technologies Department in its role as the Joint Science and Technology Office is a focal point for chemical and biological scientific and technical expertise.[8]

- The Nuclear Technologies Directorate (RD-NT) is a group that may present near-term transition opportunities. DTRA RD-NT has an expressed need for technologies that improve the ability to detect nuclear and radiological threats.[9]

DTRA also participates in Broad Agency Announcements (BAA) to identify, adopt, and adapt emerging and revolutionary sciences that may demonstrate high payoff potential to counter-WMD threats. Companies with applicable novel or revolutionary concepts or products are encouraged to contact DTRA.

2.2.2. Joint Program Executive Office for Chemical, Biological, Radiological and Nuclear Defense

The Joint Program Executive Office for Chemical, Biological, Radiological And Nuclear Defense (JPEO- CBRND) is a joint program office with each service (Navy, Army, Air Force, Marines) having unique roles with respect to technology development, testing, acquisition, and capabilities development.[10] The program spans across all services, addressing the detection and security needs for military facilities and installations.[11] JPEO-CBRND leads, manages, and directs the acquisition, fielding and sustainment of CBRN sensors, protective equipment, medical countermeasures, information management systems, defense enabling biotechnologies, and specialized equipment.[12] The Figure below provides an overarching overview of the organization.

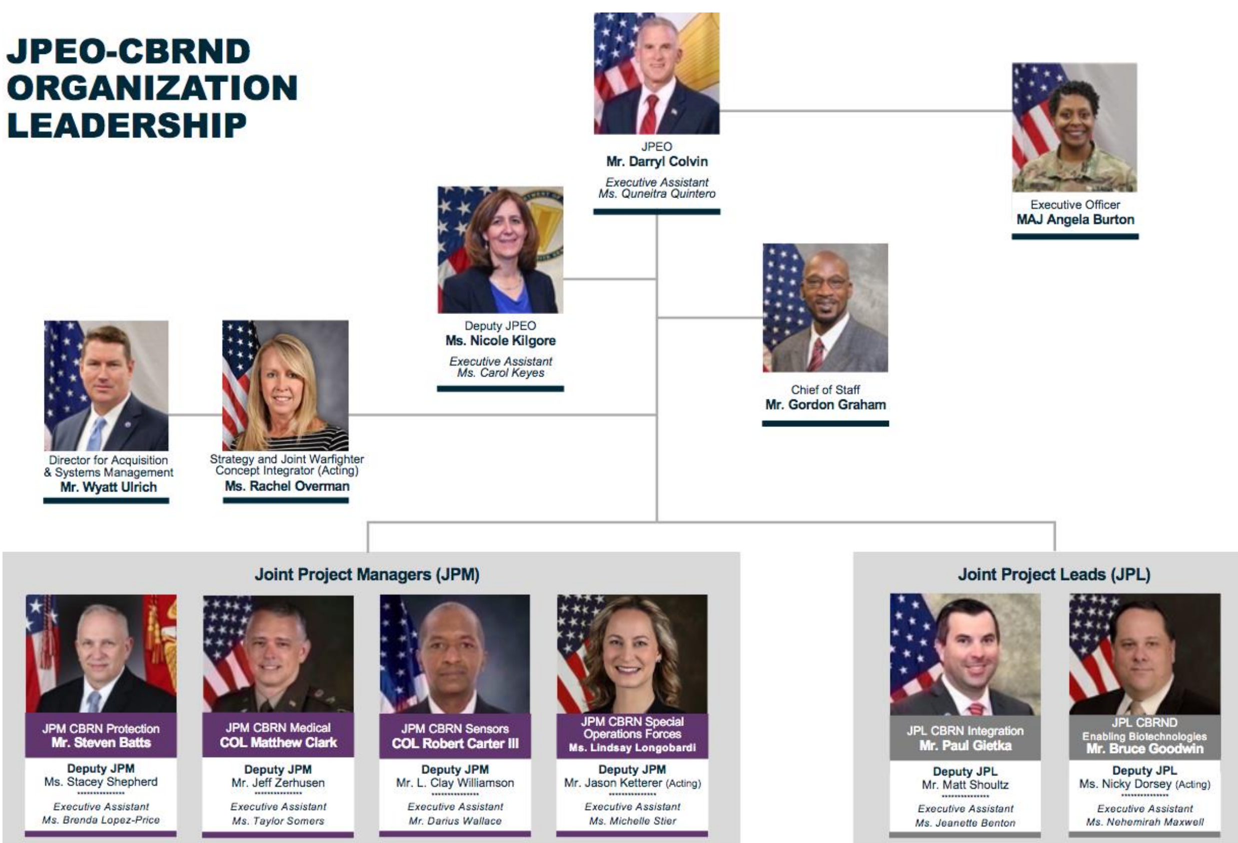


Figure 2: JPEO CBRND Organization

Source: Joint Program Executive Office for Chemical, Biological, Radiological and Nuclear Defense "Command Brief." (January 2024)[13]

JPEO CBRND supports research, development and sale of chemical, biological, radiological, nuclear (CBRN), and high-yield explosives defense systems, capabilities, equipment, supplies and material.

Figure 3: JPEO CBRND Organization
Source: Dr. Jason W. Roos. "Command Brief." (September 2021)[14]

Three Joint Project Managers (JPM) provide oversight for the portfolios that are relevant to this topic are:

1. **JPM CBRN Protection** – develops, fields and sustains CBRN protection and increase mitigation capabilities for the Nation
2. **JPM CBRN Medical**
3. **JPM CBRN Sensors** – develops, fields and sustains CBRN sensors, reconnaissance systems, mobile laboratory systems and obscuration capabilities for the Army.[15]

For companies looking to engage JPEO CBRND, recommended entry points include:

- Industry days
- Conferences
- Office calls
- Chemical Biological Defense Acquisition Initiatives forum
- NBC Industry Group[16]

Also noteworthy is, SPARK – JPEO CBRND idea incubator, through which JPEO CBRND provides funding for transformative projects.

2.2.3. Naval Surface Warfare Center - Chemical, Biological, Radiological Defense (CBR-D)

Naval Surface Warfare Center Indian Head Division (NSWC IHD) is one of 10 warfare center divisions within the Naval Sea Systems Command Enterprise. NSWC IHD brings together a full-spectrum energetics facility in the DoD with a large concentration of explosive ordnance disposal technology and resources. NSWC IHD is dedicated to energetics and explosive ordnance disposal.[17] Some of the capabilities include:

- Explosive ordnance disposal unmanned systems
- Conventional and improvised weapons exploitation
- Chemical, Biological, and Radiological Defense Systems[18]

Naval Surface Warfare Center Naval Surface Warfare Center Dahlgren Division conducts advance research in all systems-related areas and pursues scientific disciplines including physics, mathematics, directed energy and digital engineering, modeling and simulation, software, mechanical, electrical and systems engineering.[19] Their strategic direction is to provide the full spectrum of science and engineering capabilities for surface ship weapons systems integration up to the force level, missile defense, strategic systems and related areas of joint and homeland defense.[20] The Chemical Biological Radiological Defense Division serves as the technical expert and systems engineer for Navy CBR Defense.[21]

2.2.4. Army – Combat Capabilities Development Command (CCDC) – Chemical Biological Center (DEVCOM Chemical Biological Center)

U.S. Army Combat Capabilities Development Command (DEVCOM) conducts and sponsors scientific research in areas important to the Army, develops scientific discoveries into new technologies.[22] Within CCDC, the DEVCOM Chemical Biological Center is the primary DoD technical organization for non-medical chemical and biological defense. Its mission is to "provide innovative chemical, biological, radiological, nuclear and explosive defense capabilities."[23]

2.2.5. Irregular Warfare Technical Support Directorate (formerly Combating Terrorism Technical Support Office)

The mission of the Irregular Warfare Technical Support Directorate (IWTSD) is to identify and develop capabilities for DoD to conduct Irregular Warfare against all adversaries, including Great Power competitors and non-state actors, and to deliver those capabilities to DoD components and interagency partners through rapid research and development, advanced studies and technical innovation, and provision of support to U.S. military operations."[24]

Focus areas include,

> "conduct analysis to better understand and predict the CBRNE operating environment, threats, and vulnerabilities. Develop tools that proactively analyze, aggregate, and integrate multi-source data to enhance the operational effectiveness of CBRNE operators and First Responders. … Reinforce security by developing capabilities to detect and locate weapons of mass destruction and other CBRNE threats. Enable CBRNE operations to identify threats and contaminated areas. Support stabilization efforts with tools to rapidly confirm safe return to areas after decontamination."[25]

2.3. Department of Homeland Security

Department of Homeland Security (DHS)'s efforts and resources that are devoted to developing more advanced integrated passenger screening technologies for the most effective security of passengers and baggage. DHS manages several programs and activities designed to prevent and protect against domestic nuclear, radiological, biological and chemical agent attacks. Some DHS components have programs that focus on chemical /radiological and nuclear defense, such as the National Protection and Programs Directorate, the Science and Technology Directorate's (S&T) chemical hazard characterization.[26] Others have responsibilities as part of their broader missions, such as U.S. Customs and Border Protection, Transportation Security Administration, the Federal Emergency Management Agency and the U.S. Coast Guard.

Nuclear/radiation detection is important to DHS. Detection devices such as Personal Radiation detectors, Radioactive Isotope Identification Devices, radiation portal monitors and Non-Invasive Imaging systems) are commonly used in airports, courthouses, government buildings, nuclear plants and other sensitive areas to scan people, luggage and shipping containers for weapons. The presence of nuclear weapons can be detected by gamma ray and neutron signatures of radioactive isotopes. Thus, detection technologies that would allow neutron detection with an ability to discriminate gamma events from neutron events would be of interest to DHS.

Detection: Passenger Screening, Baggage Screening, Cargo Screening Locations: ports; airports; ports of entry; mass transit

Applications:

- High-throughput cargo screening
- Electronic imaging for bulk air cargo
- Rapid detection of explosives
- Accurate detection of complex threat concealment on passengers and carried property

DHS S&T invests in sensors, screening systems and detection devices to address homeland security needs such as screening for explosives.[27] For example, the Surface Transportation Explosive Threat Detection program develops technologies to secure mass transit systems.[28]

2.3.1. Countering Weapons of Mass Destruction Office (CWMD)

DHS CWMD office conducts, supports, and coordinates an R&D program to address significant technical challenges unresolved by current capability. This includes the development of technologies that will have an impact on the ability to detect WMD threats.

CWMD manages several programs specific to its mission to protect the U.S. against chemical, biological, radiological, and nuclear attacks.[29] For example, CWMD manages the program to acquire handheld detectors for the U.S. Coast Guard and replacements for radiation portal monitors that Customs and Border Patrol operates at high-volume ports.[30] The mission of the CWMD Office is "provide operators and analysts with the advanced tools and capabilities needed to execute the CWMD mission by investing in transformational R&D." One of the R&D goals addresses detection:

> Detecting and identifying CBRN materials quickly and accurately is core to executing the CWMD mission. Although techniques and technologies currently exist, particularly in laboratory settings, they are not necessarily suitable for the needs of field operations. Some of the most effective technologies are prohibitively expensive for widespread deployment. Investments that will bring down per-unit costs while maintaining or increasing performance will bring dividends in detection coverage and mission effectiveness.

- **Objective 1.1:** Improve detector and trigger materials and components.
- **Objective 1.2:** Explore alternative signatures.
- **Objective 1.3:** Decrease the time to detect and identify.

- **Objective 1.4:** Model sensor behavior.[31]

Some of the R&D needs identified for the period in 2020:

> **"Goal 1: Improve and decrease costs of sensors**
> For CBRN research, there will be a continued effort to improve the capabilities of deployed sensors while reducing their cost. Detecting and identifying CBRN materials quickly and accurately is core to executing the CWMD mission.
>
> A primary focus of R/N threats will continue to be the development of materials that detect gamma rays and/or neutrons, because these materials drive the costs of detection systems. Previous years' efforts have resulted in great advancement in such materials, and further improvements still can be made. Another key focus will be sources of x-rays for inspecting cargo and vehicles for dense objects, which may be indicative of attempts to shield radioactive or nuclear material.
>
> Near-term R&D needs associated with Goal 1:
>
> 1. Semiconductor and scintillator materials science for R/N detection,
> 2. Compact emission generators (e.g., x-rays, neutrons) for visualization of contents in sealed containers."[32]

CWMD customers include DHS operational Components (such as Transportation Security Agency, U.S. Coast Guard and Customs & Border Patrol), and federal, state, local, and tribal responders.[33]

2.3.2. Transportation Security Administration (TSA)

TSA has approximately 14,200 transportation security equipment units deployed at approximately 440 airports.[34] TSA continues to advance aviation security by enhancing existing technologies and acquiring and integrating new technologies to screen passengers and checked baggage more effectively and efficiently. TSA responsibilities include security screening of passengers and baggage at approximately 440 airports in the United States.[34] TSA identifies, tests, procures, deploys, upgrades, and maintains a variety of equipment to screen passengers and their carry-on baggage at airports. Current checkpoint technologies include:

- Advanced Imaging Technology
- Advanced Technology X-Ray
- Bottled Liquid Scanners
- Enhanced Metal Detectors

- Explosives Trace Detectors.[35]

In terms of selling to the TSA, information found at this link provides insights on doing business with TSA. It takes time for TSA to fully qualify a new technology. For example, public announcement pertaining to a contract for 3D scanners awarded to Smiths Detection for 300 Computed Tomography (CT) scanners and associated ancillary equipment reported that, there was an extensive evaluation process involved in the determination of a final acquisition; part of which is captured in the image below. Also note that, "in making its final decision, TSA weighed several factors to include successful field and lab tests, production capability, and the ability to upgrade the systems, as well as price."[36] The process used to evaluate the technology is shown in Figure 4 on the next page.

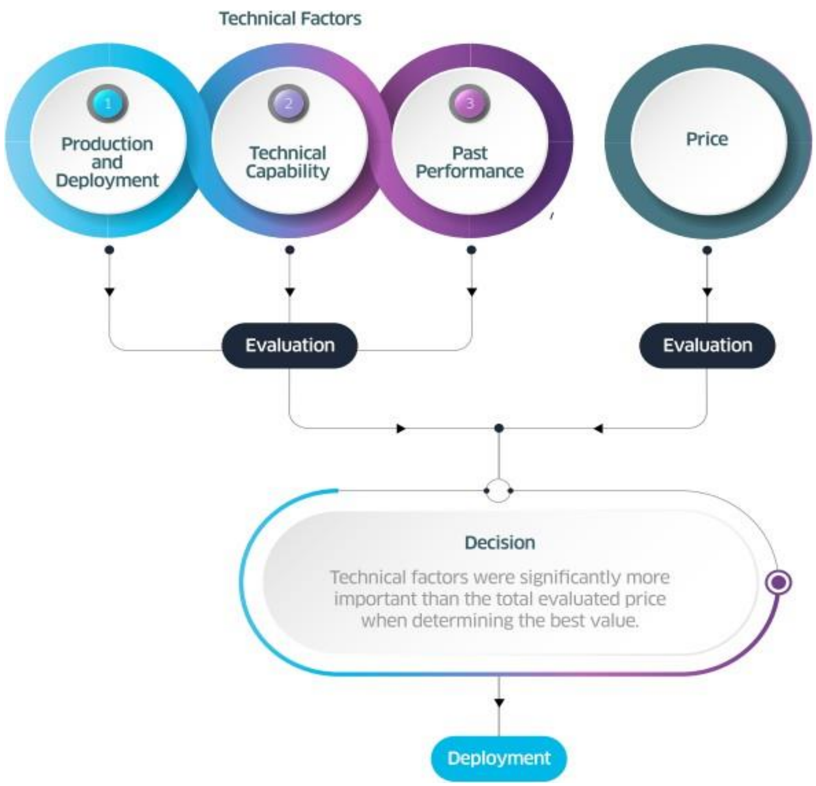


Figure 4: TSA, Evaluation Process for a CT Scanner Award
Source: TSA. "Evaluation Process for Initial CT Award."[37]

TSA technology acquisition process which takes several steps begins with standards:

> TSA develops detection standards that identify and describe the prohibited items—such as guns, knives, military explosives, and homemade explosives—that each technology is to detect during the screening process. The standards, which are classified, also identify how often the technology should detect prohibited items (referred to as the required probability of detection) and the maximum rate

at which the technology incorrectly identifies prohibited items (the probability of false alarm).

After a detection standard is approved, TSA decides whether to operationalize—put into effect—detection standards by acquiring and deploying technologies to update detection capabilities to meet the standard. That is, it decides whether to take steps to develop new technology capable of meeting the standard and put the new technology in place at commercial airports. Technology can mean new software to upgrade existing screening systems as well as entirely new screening systems. TSA does not always or immediately operationalize detection standards.

Once manufacturers have developed new technologies that meet detection requirements, the technologies undergo a test and evaluation process, known as the qualification process. The following are key steps in that process:

a. Certification – Certification is a preliminary step in TSA's qualification process. For TSA to certify that a screening technology meets its detection requirements, S&T's Transportation Security Laboratory conducts certification testing on a manufacturer's initial submission of its proposed screening technology to determine whether it meets TSA's detection requirements (i.e., the rate at which it must accurately detect each category of explosive it is designed to detect, among other things).

b. Integration/Implementation Testing – TSA Systems Integration Facility administers qualification testing to test system performance against additional requirements, such as reliability, availability, and maintainability. TSA also conducts field testing to ensure readiness for operational test and evaluation.

c. Operational Test and Evaluation - TSA deploys units to selected airports to conduct operational testing. Operational testing allows TSA to evaluate the operational effectiveness, suitability, and cyber resiliency of the technology in a realistic environment.

After new technologies have been tested and approved, TSA can purchase and deploy them to commercial airports. When a deployed screening system can no longer be updated to meet new detection standards, TSA considers it obsolete and generally designates it for replacement with a newer version of the technology.[38]

Figure 5 shows TSA's process for acquiring and deploying new screening technologies to meet detection standards.

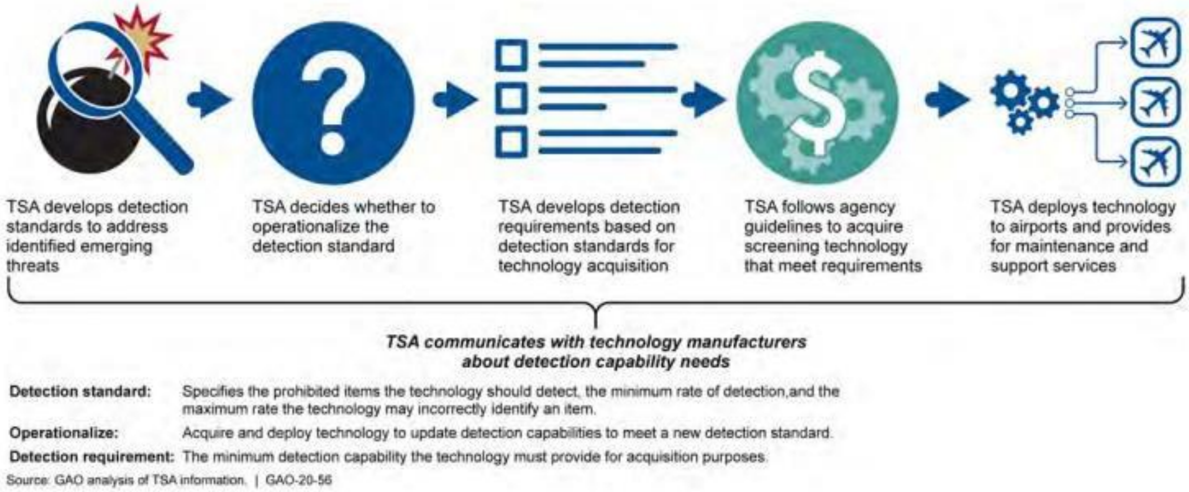


Figure 5: TSA's Process for Acquiring and Deploying New Screening Technologies
Source: Government Accountability Office. "Aviation Security." (December 2019)[39]

TSA regularly assesses commercially available technologies. In addition, TSA works in collaboration with DHS Science & Technology and industry to develop new capabilities.

2.3.3. Customs & Border Patrol (CBP)

Customs and Border Patrol (CBP) has extensive inspection facilities within the United States and purchases screening equipment. CBP, a department within the DHS is the lead federal agency charged with a dual mission of facilitating the flow of travel and trade at US borders as well as border protection. CBP inspects passenger vehicles, pedestrians, and commercial vehicles at U.S. land ports of entry. Ports of entry are facilities that provide for the controlled entry into or departure from the United States. Specifically, a port of entry is any officially designated location (seaport, airport, or land border location) where CBP officers or employees are assigned to clear passengers, merchandise and other items, collect duties, and enforce customs laws. **CBP operates 328 ports of entry at which it inspects inbound cargo, including express cargo and mail**. CBP coordinates with other federal agencies—including TSA, the U.S. Postal Inspection Service, and the Food and Drug Administration to assess the compliance of inbound items.[40]

The Border Patrol utilizes a variety of equipment and methods, such as electronic sensors to detect people or vehicles entering the country illegally. CBP acquires inspection equipment such as large-scale X-ray and Gamma ray imaging systems, as well as a variety of portable and handheld technologies. CBP's nuclear and radiological detection equipment includes radiation portal monitors, radiation isotope identification devices, and Personal Radiation Detectors.[41] Large scale and small scale non-intrusive inspection imaging systems for examining large conveyances such as cars, trucks, buses, rail cars, and sea containers. CBP's Office of Field Operations and the Border Patrol are now the primary users of this equipment (Border Patrol obtains equipment through Office of Field Operations) for use at designated checkpoints. Large scale non-intrusive inspection systems include both fixed and mobile units. In November 2023 it was reported CBP had approximately 206 mobile units are in CBP's non-intrusive inspection fleet. The average age of these systems is 7 years old, and 36 percent of the fleet has exceeded its estimated useful life of 10 years. CBP reported having more than 370 large scale non-intrusive inspection imaging systems.[42]

CBP Office of Field Operations

CBP plays a vital role in interdicting illicit narcotics before they enter into the United States. CBP's Office of Field Operations is responsible for inspecting pedestrians, passengers, vehicles, and cargo at 110 land points of entry, which have a combined total of 173 crossings. 12 field offices oversee all types of points of entry—air, sea, and land.[43]

Laboratories and Scientific Services Directorate (LSDD)'s Interdiction Technology Branch is the technical authority responsible for the acquisition, initial deployment, train-the-trainer testing, and evaluation of small-scale non-intrusive inspection.45 "LSSD has eight regional laboratories, one 24x7 Teleforensics Center, and one Interdiction Technology Branch supporting over 200 scientists, chemists, biologists, textile analysts, physicists, forensic scientists, engineers, and procurement specialists. The CBP laboratories vary in their specialties based on location and conduct scientific analysis of a broad spectrum of chemical, biological, and manmade products to ensure compliance with U.S. federal laws."[44]

2.3.4. U.S. Coast Guard

The Coast Guard is responsible for search and rescue; port, waterway, and coastal security; and homeland defense readiness. The Coast Guard conducts vessel inspections; performs incident response, including incidents involving oil or chemical releases; and interdicts drugs and hazardous material in the coastal zones and navigable waterways of the United States and its territories.[45] The US Coast Guard Border Patrol obtains equipment through CWMD and does not appear to have its own R&D efforts for radiation/nuclear detection.

2.4. National Aeronautics and Space Administration (NASA)

NASA has refocused its attention to conducting sustainable exploration missions to the moon, specifically, "Lead an innovative and sustainable program of exploration with commercial and international partners to enable human expansion across the solar system and to bring back to Earth new knowledge and opportunities. Beginning with missions beyond low-Earth orbit, the United States will lead the return of humans to the Moon for long-term exploration and utilization, followed by human missions to Mars and other destinations."[46] In a NASA press release dated April 9, 2019, "Sending American Astronauts to Moon in 2024: NASA Accepts Challenge," NASA expressed its commitment to a timeline of landing humans on the lunar south pole by 2024. The lunar exploration plans are based on a two-phased approach: (1) landing astronauts on the Moon in five years and, (2) establish a sustained human presence on and around the Moon by 2028. NASA will use an orbiting lunar outpost called Gateway to access the Moon.[47] To accomplish this, NASA is investing in many technologies including radiation detection.

2.4.1. Space Radiation Analysis Group (Johnson Space Center)

As NASA prepares to send humans to the Moon and on to Mars, NASA, has been advancing radiation detection instrumentation.[48] The Space Radiation Analysis Group (SRAG) at the Johnson Space Center is "responsible for ensuring that the radiation exposure received by astronauts remains below established safety limits. To fulfill this responsibility, the group provides:

- Radiological support during missions.
- Pre-flight and extra-vehicular activity (EVA) crew exposure projections.
- Evaluation of radiological safety with respect to exposure to isotopes and radiation producing equipment carried on the spacecraft.
- Comprehensive crew exposure modeling capability.
- Radiation instruments to characterize and quantify the radiation
- environment inside and outside the spacecraft."[49]

2.4.2. NASA Glenn Research Center

The NASA Glenn Research Center is developing radiation detectors based on wide band-gap semiconductors to meet the challenges of low-power, low-noise, multidirectional robust detectors for a wide range of particle mass and energies. "The advanced space radiation detector development team at NASA Glenn Research Center has the goal of developing unique, more compact radiation detectors that provide improved real-time data on space radiation."[50]

2.5. Academic Institutions and Neutron Radiography Applications

Novel gas and solid-state detectors may find applications in neutron radiographic imaging. Neutron radiography is a commercially available service, used in the aerospace industry for the testing of turbine blades for airplane engines, components for space programs, high reliability explosives, and to a lesser extent in other industry to identify problems during product development cycles. Nuclear radiography has not been fully realized due to several inherent disadvantages of working with radioactive isotopes. The regulatory controls, the increasing costs to maintain these sources, and the issue of half-life losses are some of the reasons cited for the lack of market penetration.[51] In addition, the move from laboratory to industry has been hampered by the generally large neutron flux requirements and by the relatively small number of nuclear research reactors.[52] Neutron imaging has been underused for inspecting devices such as ejection and payload fairing separation mechanisms since most facilities are not equipped to handle energetic material.[53]

Although there are many potential applications for neutron radiography, our extensive research indicates that traditionally, neutron radiography studies have been performed at governmental or university neutron research centers and this continues to be the case currently. However, some companies such as Applus+ and Phoenix LLC are making inroads by opening neutron radiography centers. Similar to X-ray radiography, neutron radiography has been used as a tool to enhance investigations in the field of non-destructive testing. In fact, neutron radiography is suitable for some tasks impossible for conventional x-ray radiography. Neutrons can image light elements (hydrogen, water, carbon) and can penetrate heavy elements (lead, titanium) allowing the study of materials in complex sample environments such as NDT applications within automotive and aerospace.[54]

Apart from services provided by government laboratories and universities, neutron radiography facilities, there are very few companies that are providing the service. Below are some examples. Outside of DOE national labs, nuclear research reactors are located at universities and NIST. These are listed below.

Neutron Imaging Systems at Universities in the U.S.	
University of Utah, Salt Lake City	University of Utah Nuclear Engineering Facilities "maintains the only Neutron Activation Analysis facility in Utah, which provides a highly sensitive technique for identification and quantification of major, minor and trace elements in a material sample that is non- destructive. The method of NAA requires a steady source of neutrons of required energy distribution. We provide such a source within the irradiation ports of our nuclear research reactor." The reactor facility provides has the ability for isotope production that finds wide-ranging applications in various fields, including industry, research, agriculture and medicine.[55]

Colorado School of Mines	The Nuclear Science and Engineering Center (NuSEC) supports faculty engaged in research related to Nuclear Science and Engineering at The Colorado School of Mines. "NuSEC manages the research relationship, space, and experimental infrastructure used by Mines faculty and researchers at the US Geological Survey's TRIGA Mark I reactor facility at the Denver Federal Center in Lakewood, CO. The reactor laboratory houses experimental systems for gamma spectroscopy, neutron activation analysis and neutron radiography. Colorado School of Mines laboratory space at the Denver Federal Center is home to electron and optical microscopy facilities for nuclear materials analysis, as well as wetlab space for chemical analysis. The TRIGA reactor is also used in conjunction with a graduate course in reactor operations that is taught by senior reactor operators."[56]
Texas A&M University, College Station	The centerpiece of the Nuclear Science Center is a 1-megawatt TRIGA reactor, an open "swimming pool"-type research reactor cooled by natural convection providing passive and inherent safety. The core consists of cylindrical fuel elements reflected with graphite.[57]
Penn State University	Facilities include the Penn State Breazeale Reactor, gamma-ray irradiation facilities (in- pool irradiator and dry irradiator), the Neutron Beam Laboratory, the Hot Cell Laboratory, the Radionuclear Applications Laboratory, the Radiochemistry Teaching Laboratory, the Nuclear Security Education Laboratory, the Subcritical Graphite Reactor Facility, and various radiation detection and measurement laboratories.[58] The Radiation Science and Engineering Center has a facility specifically designed to measure the 10B concentration in neutron-absorbing materials.[59]
Rensselaer Polytechnic Institute	Gaerttner Linear Accelerator Center at Rensselaer Polytechnic Institute is a major research center in the school of engineering. The center is supported grants of faculty from the Nuclear Engineering Program which is in the department of Mechanical Aerospace and Nuclear Engineering. The laboratory welcomes industrial R&D in radiography. At Rensselaer there are X-ray sources that range from 25 keV to 250 keV with hard tube generators to the multi-MeV intense bremsstrahlung source from the electron LINAC.
University of Maryland	The University of Maryland Radiation Facilities is located at the flagship campus of the University of Maryland in College Park. It is home to a 250kW TRIGA Reactor, a Panoramic Co-60 Irradiator, an Electron Linear Accelerator, and a Cyclotron.[60]

MIT Nuclear Reactor Lab	The MIT Nuclear Reactor Lab has an extensive array of facilities for performing neutron and gamma irradiations, for studying neutron physics, and for examining radioactive materials. The MITR has two neutron scattering facilities.[61]
Kansas State University	The Kansas State University TRIGA Mark II nuclear reactor facility supports academic and education programs, research, industrial service and outreach. The reactor is licensed to operate at up to 1.25 MW. Its research capabilities include a variety of neutron beams for detector testing, internal imaging using neutron radiography and tomography, tracer isotope production, and trace element analysis via neutron activation analysis. The facility is staffed almost entirely by licensed undergraduate student operators, providing both an excellent opportunity for the students and supporting the manpower needs of the local nuclear power industry.[62] Experiments: • Neutron activation analysis using HPGe spectrometers • Neutron irradiation: nvt = ~1E8 – 1E18 neutrons/cm2 • Gamma irradiation: up to ~500 krad/hr. for samples below 50 mL in size, and up to ~1 krad/hr. for samples up to 20 L in size • Neutron radiography • Neutron detector testing: four beam ports with distinct neutron spectra, and Cf-252 neutron/gamma source.[63]
University of Texas at Austin - Nuclear and Radiation Engineering Program	The reactor, designed by General Atomics, is a TRIGA Mark II nuclear research reactor. The NETL is the newest of the current fleet of U.S. university reactors. The NETL reactor has in-core irradiation facilities and five beam ports. The reactor is capable of steady-state operation at power levels up to 1 MW or pulsing mode operation where powers as high as 1500 MW are achieved for about 10 msec.
University of Wisconsin – Madison	The University of Wisconsin-Madison Engineering Physics department has a 1 MW TRIGA research reactor, called the University of Wisconsin Nuclear Reactor (UWNR). The UWNR is operated as a teaching and research reactor since 1961. University of Wisconsin TRIGA Reactor, a 1 MW facility provides capabilities in neutron activation analysis as well as neutron radiography and radiolysis.[64] The lab supports a wide range of research and educational endeavors including the Engineering Physics department, other departments of the university, and both external educational and non-educational institutions across the United States.[65]

North Carolina |State University	The Neutron Imaging Facility is installed at beamport #5 of the PULSTAR reactor, which provides a nominal source flux of 2.5×1012 n/cm2/sec at 1 MW. The beam is collimated and filtered with 12 inches of single crystal sapphire.[66]
Oregon State University	Completed in 2004, the Neutron Radiography Facility (NRF) represents a major structural expansion of the facility. The Oregon State University TRIGA Reactor (OSTR) is a water-cooled, swimming pool type research reactor which uses uranium/zirconium hydride fuel elements in a circular grid array. "The NRF is essentially a large, shielded room (8 ft X 8 ft X 9 ft) containing a highly collimated beam. The NRF utilizes beam port #3 because the tangential orientation of the beam port allows predominately thermal neutrons to stream down the tube while minimizing the amount of gamma radiation contaminating the beam. A collimator was placed in beam, port #3 to optimally collimate and filter the beam and is composed of a bismuth filter, a series of decreasing rings of lead down to a 2 cm boral aperture, and a series of increasing diameter rings. The end of the collimator contains a boral plate with a 6 x 7-inch opening to form a square emitted beam shape. The bismuth filter substantially removes the unwanted gamma radiation while being fairly transparent to thermal neutrons. Using conventional film, the beam was determined to meet the requirements of an ASTM E545 Category 1 neutron radiography beam."[67]
Rhode Island Nuclear Science Center	The Rhode Island Nuclear Science Center (RINSC) serves as the headquarters for the Rhode Island Atomic Energy Commission. Located on the University of Rhode Island's Bay campus, the RINSC is the home of Rhode Island's sole nuclear reactor. The RINSC reactor was built in 1960. It is a 2 Mega-Watt, light water cooled, pool type reactor."[68] This facility includes a 2 MW reactor to be used as a tool for education, research and service work related to the nuclear industry and technology. The long-term vision is for it to become an integral part of the national infrastructure. Plans are to upgrade the reactor to 5 MW.[69]
Washington State University	Washington State University Nuclear Radiation Center (WSUNRC) includes a 1 MW TRIGA reactor. It provides irradiation services, radioisotope production and analytical services for researchers at Pacific Northwest National Laboratory (PNNL) as well as for the radiochemistry program at WSU.[70] Produces radioisotopes for national laboratory and business clients. Includes a power pulsing capability (to 1000 MW) which has been frequently used in cooperation with PNNL). It has been used extensively for research in boron neutron capture therapy.

University of California, Davis – The McClellan Nuclear Research Center	The McClellan Nuclear Research Center (MNRC) is owned and operated by the University of California, Davis (UC Davis) and is located in Sacramento. The reactor must be used at least 51 per cent of the time for research; the remainder of the time it can be used for revenue-producing commercial work, which covers some of its operational costs.[71] "The Center was originally built by the US Air Force to detect hidden defects in aircraft structures using neutron radiography; the Center can accommodate samples as large as 10.00 m long, 3.65 m high, and weighing up to 2,270 kg. Two of the four radiography bays are laboratory-size rooms where smaller samples can be inspected using both radiography and tomography.[72]
University of Massachusetts, Lowell	A 1-Megawatt research reactor produces thermal neutrons for radioactivation purposes and for digital neutron radiography. Fast neutrons for atomic displacement research are produced by both the reactor and the 5.5 MV Pulsed van-de-Graaff accelerator.[73] UMass Lowell Research Reactor offers Digital Neutron Radiography as a quality assurance and R&D tool for non-destructive inspection of mechanical parts, electronics, and assemblies, including voids; missing/misplaced parts; corrosion or hydrogenous substances in sealed units; adhesive bonding flaws; channel blockages channels; water behavior; distribution of neutron absorbers in materials for nuclear applications.[74]
NIST Center for Neutron Research	The NIST Center for Neutron Research provides infrastructure for fuel cell manufacturers and university users to perform fuel cell experiments on both commercial grade and smaller research grade fuel cells and stacks. "NIST has operated the NCNR safely for more than 50 years, providing a premier research facility serving more than 2,500 researchers from across the U.S. each year. Their research has improved the understanding of a wide variety of materials and phenomena, helping to improve pharmaceuticals, high-tech alloys, data storage and much more."[75]
Industry Partners	Applus+ - the company has grown its neutron radiography capacity with a new facility at Oregon State University.[76] Phoenix LLC (Monona, Wisconsin) - manufactures fusion neutron generators to replace reactors for industrial radiography, radiation effects testing, and medical isotope production.[77] Starfire Industries (Champaign, IL) specializes in neutron generators and other plasma technologies across a wide range of industries.[78]

3.0 Market Size: Radiation Detection, Monitoring and Safety Market

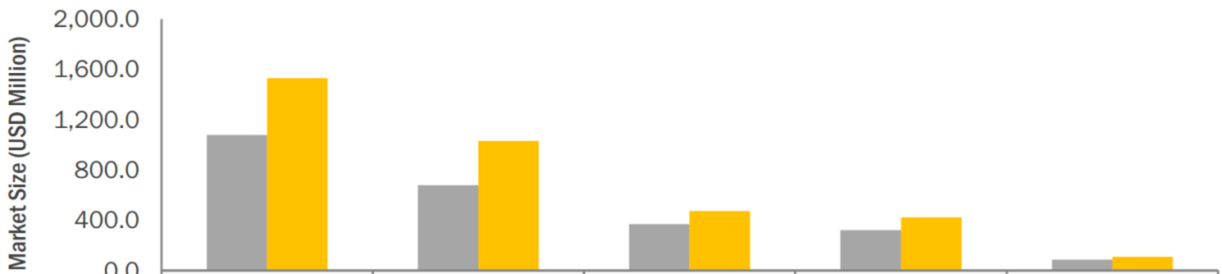
The forecast for the radiation detection, monitoring, and safety market is predicted to reach $3.5 billion by 2027 from an estimated $2.05 billion in 2020, at a CAGR of 7.1% for the five years 2022 - 2027[79] (Figure below).

Product	2020	2021	2022	2023	2024	2025	2026	2027	CAGR (2022–2027)
Radiation Detection and Monitoring Products	1,546.2	1,741.8	1,915.4	2,071.6	2,219.6	2,380.3	2,555.0	2,744.9	7.5%
Radiation Safety Products	506.6	563.0	610.7	651.6	688.7	728.7	771.7	817.9	6.0%
Total	2,052.9	2,304.8	2,526.1	2,723.1	2,908.3	3,109.0	3,326.6	3,562.8	7.1%

Figure 6: Global Radiation Detection, Monitoring, and Safety Market by Application, 2022 vs 2027 (USD Million)

Source: Reprinted with permission from MarketsandMarkets[80]

Market drivers identified by MarketsandMarkets include increase in security threats, increasing safety awareness among people working in radiation-prone environments, growing safety concerns post the Fukushima disaster, growing security budgets for global sporting events, growth in the number of PET/CT scans, increasing usage of nuclear medicine and radiation therapy for diagnosis and treatment, and use of drones for radiation monitoring.[81]



	Healthcare	Homeland Security & Defense	Industrial Applications	Nuclear Power Plants	Other Applications
2022	1,077.4	677.5	367.1	319.1	84.9
2027	1,530.7	1,029.4	472.9	421.6	108.3
CAGR	7.3%	8.7%	5.2%	5.7%	5.0%

Figure 7: Global Radiation Detection, Monitoring, Safety Market Application, 2022 vs 2027 (USD Million)

Source: Reprinted with permissions from MarketsandMarkets[82]

A sample of companies active in this market include Teledyne FLIR Systems, Thermo Fisher Scientific, Mirion Technologies (which merged with Canberra Industries), Kromek, Landauer, ORTEC, General Electric, Ludlum Measurements, and many others.[83]

Some of the key players in the global radiation detection market are Thermo Fisher Scientific, Inc., Protech Radiation Safety, Bar-Ray Products, Inc., ProtecX, Landauer, Inc., Ametek, Inc., Mirion Technologies, Inc., Biodex Medical Systems, Inc., and others.[84]

4.0 Technology for Rare Decay and Rare Particle Detection

Nuclear physics research has a need for devices to detect, analyze, and track photons, charged particles, and neutral particles such as neutrons, neutrinos, and single atoms. DOE is specifically looking for a variety of technologies with the following specs/parameters:

- Detectors based on uniquely quantum properties such as superposition, entanglement, and squeezing

1. Detectors with very high resolution (tenths of micrometers spatial resolution and tenths of eV energy resolution)
2. Bolometers, including the required thermistors
3. Ultra-low background techniques and materials
4. Ultra-sensitive assay or mass-spectrometry methods for quantifying contaminants in ultra-clean materials
5. Cost-effective production of large quantities of ultra-pure liquid scintillators
6. Novel methods capable of discriminating between interactions of gamma rays and charged particles in rare event experiments
7. Background interactions in rare event searches, such as those induced by gamma rays or neutrons, can be tagged, reduced, or removed entirely.

Potential Applications and Partners

- Opportunities exist for developing equipment beyond the present state-of- the-art needed at universities, national scientific user facilities, and facilities worldwide. Also of interest is technology related to future experiments in fundamental symmetries, such as neutrinoless double- beta decay.
- rare-kaon experiments such as KOTO, and at the Cosmic Frontier in cryogenic LiAr and LiXe dark-matter searches.
- NASA – agency that deals with neutrino detection - only government agencies have the facilities for studying neutrino, as neutrino detection is so rare
- Universities - neutrino detection may be enabling technology for particle physics communities at universities
- Companies that specialize in nano materials in extremely clean rooms, such as semiconductor manufacturers.

4.1. Dark Matter and Neutrino Studies

Dark matter studies require extremely sensitive detectors. There are several experiments around the world studying dark matter that require ultra-sensitive equipment.[85] "Scientists have been trying to create dark matter particles by crashing two high-energy protons into one another in the Large Hadron Collider, mimicking what might have occurred at the Big Bang when all these particles formed. However, direct detection experiments hope that dark matter particles occasionally interact with normal matter via the weak force, allowing them to be spotted by extremely sensitive detectors. Since the characteristics of dark matter particles are completely unknown, researchers trying to detect dark matter directly essentially make an educated guess about what mass their detectors should be looking out for."[86]

Table 4: Dark Matter Studies

Activities and Potential Partners in the US	
U.S. – NSF/DOE Funded	LUX-ZEPLIN experiment aims to directly detect dark matter. projects hope to tackle the challenge using systems with unprecedented scale and sensitivity.[87] The LZ collaboration consists of about 250 scientists in 35 institutions in the U.S., U.K., Portugal, and Korea. The Sanford Underground Research Facility is the lead.[88]
U.S. – NSF and DOE Funded	Super Cryogenic Dark Matter Search (SuperCDMS) is a collaboration between several institutions performing experiments to directly detect dark matter. SLAC National Accelerator Laboratory has overall responsibility for the detector payload (detectors and associated cryogenic mechanics and electronics) and offline computing for the experiment.[89]
DOE Funded	Axion Dark Matter Experiment (ADMX) uses a resonant microwave cavity within a large superconducting magnet to search for cold dark matter axions. Sited at the Center for Experimental Nuclear Physics and Astrophysics (CENPA) at the University of Washington, ADMX is a large collaborative effort with researchers from universities and laboratories around the world.[90]
	Another interesting program is the next generation of NSF/DOE supported CMB survey instruments (CMB-S4). CMB-S4 experiment is planned as a joint DOE and NSF project. The CMB-S4 collaboration now numbers 236 members at 93 institutions in 14 countries and 21 U.S. states.[91] The project is hoping to deploy its first telescope in 2027.[92]
Potential International Partners International institutions and research groups are also active in dark matter research. For example, Italy and China is very active in the field of neutrino research. Examples include: **1. XENON project (Italy)** **2. PandaX-II (China)**	
International	The XENON dark matter research project, operated at the Italian Gran Sasso National Laboratory. The XENON experiment is a 3500kg liquid xenon detector to search for the elusive Dark Matter. The XENON1T detector was filled with 3.2 tons of ultra-pure liquefied xenon. XENON1T is now upgrading to its next phase–XENONnT–with an active xenon mass three times larger and a background that is expected to be lower than that of XENON1T.[93]
	(Shanghai Jiao Tong University, China) is a series of experimental projects that utilizes Xenon detectors to search for dark matter particles and to understand the fundamental properties of neutrinos. The PandaX collaboration has now entered the multi-ton stage of the project, PandaX-4T.[94]

	Other applications include investigations of rare decays is SuperNEMO in Laboratoire Souterrain de Modane (France).[95] The SuperNEMO detector construction in on going and will consists of 20 modules each containing approximately 5 kg of enriched double beta decay emitting isotope.[96] One of the key challenges of the SuperNEMO detector development program was to improve the energy resolution of its calorimeter. The University College London group developed a detector with a resolution of 3% (σ at 1 MeV) for a calorimeter composed of large volume plastic scintillator blocks coupled to photomultiplier tubes. This technology went beyond SuperNEMO and is currently being adapted for proton therapy applications.[97]
	Large Synoptic Survey Telescope (LSST, Cerro Pachon ridge, Chile)
	SuperCDMS-SNOLAB, is in the process of installing larger iZIPs and the new HV detectors in a shield and cryostat at the deeper SNOLAB site in Sudbury, Canada. has been funded jointly by the NSF, DOE and CFI in Canada to instrument an initial payload of 28 kg consisting of Ge iZIP (14 kg), Si iZIP (1.2 kg), Ge HV (11.2 kg) and Si HV (2.4 kg) detectors in a new facility in SNOLAB.

Table 5: Neutrino Studies

Neutrino Studies

NASA	NASA's space astrophysics missions and develop the scientific basis for future missions. NASA's Astrophysics topics include the formation of stars and planets, supernova explosions and gamma-ray bursts, the birth of galaxies, dark matter, dark energy, and the cosmic microwave background. NASA's missions including NASA's Hubble and Roman Space Telescope add pieces to the dark matter puzzle.[98] Companies working on the Romans Space Telescope include Ball Aerospace and Technologies Corporation (Boulder, CO), L3Harris Technologies (Melbourne, FL), and Teledyne Scientific & Imaging (Thousand Oaks, CA).[99] Neutrinos are fundamental particles that far outnumber all the atoms in the universe but rarely interact with other matter. NASA is particularly interested in high-energy neutrinos, which have energies up to 1,000 times greater than those produced by the most powerful particle colliders on Earth. In April 2021, NASA's Innovative Advanced Concepts program awarded a $2 million grant to Dr. Nick Solomey, Wichita State professor to study, "Cube-Sat Space Flight Test of a Neutrino Detector." According to a NASA Press release, "neutrinos are one of the most abundant particles in the universe but are challenging to study since they rarely interact with matter. Therefore, large and sensitive Earth-based detectors are best suited to detect them."[100]
IceCube Neutrino Observatory University of Wisconsin (Madison)	IceCube Neutrino Observatory at the University of Wisconsin (Madison) searches for neutrinos. IceCube, the South Pole neutrino observatory, is a cubic-kilometer particle detector made of Antarctic ice and located near the Amundsen-Scott South Pole Station. The National Science Foundation provided the primary funding for the IceCube Neutrino Observatory, with assistance from partner funding agencies around the world.[101] The University of Wisconsin– Madison is the lead institution with more than 40 partners.
Astronomy with a Neutrino Telescope and Abyss Environmental RESearch	ANTARES operating since 2008 is optimized for the detection of muons from high-energy astrophysical neutrinos residing 2.5 km under the Mediterranean Sea off the coast of Toulon, France.[102]

Baikal Deep Underwater Neutrino Telescope	The Baikal Deep Underwater Neutrino Telescope (BDUNT) is a neutrino detector conducting research below the surface of Lake Baikal (Russia) since 2003.[103]
Borexino	Borexino (located at Laboratori Nazionali del Gran Sasso) in Italy is a particle physics experiment to study low energy (sub-MeV) solar neutrinos. The detector is the world's most radio-pure liquid scintillator calorimeter. And is supported by an international collaboration with researchers from Italy, the United States, Germany, France, Poland, Russia and Ukraine.
Carbon Hydrogen AntiNeutrino Detector with a Lithium Enhanced Raghavan-optical-lattice	CHANDLER is located at Virginia Tech. "The CHANDLER detector technology is comprised of cubes of wavelength shifting plastic scintillator cubes and thin sheets of lithium-6 (6Li) loaded zinc sulfide scintillator. The 6 cm cubes are arraigned in layers of up to 20×20 cubes which are separated by the 6Li-loaded ZnS sheets."[104]
Helium and Lead Observatory	The Helium And Lead Observatory (HALO) is a neutrino detector at SNOLab for the Supernova Early Warning System in in the Creighton Mine in Sudbury Ontario Canada.
Iron Calorimeter Detector @ India- based Neutrino Observatory	India-based Neutrino Observatory (INO) is a particle physics research project under construction to primarily study atmospheric neutrinos in 1,200 meters (3,900 ft)[1] deep cave under INO Peak near Theni, Tamil Nadu, India.
Jiangmen Underground Neutrino Observatory	The Jiangmen Underground Neutrino Observatory (JUNO) is a medium baseline reactor neutrino experiment in China.
Kamioka Liquid Scintillator Antineutrino Detector	The Kamioka Liquid Scintillator Antineutrino Detector (KamLAND) is an electron antineutrino detector at the Kamioka Observatory, an underground neutrino detection facility in Hida, Gifu, Japan.

Reactor Experiment for Neutrino Oscillation	The Reactor Experiment for Neutrino Oscillation (RENO) is a short baseline reactor neutrino oscillation experiment in South Korea. The experiment was designed to either measure or set a limit on the neutrino mixing matrix parameter θ13, a parameter responsible for oscillations of electron neutrinos into other neutrino flavors.
STErile neutrino REactor Oscillation experiment	The STEREO experiment (Search for Sterile Reactor Neutrino Oscillations) investigates the possible oscillation of neutrinos from a nuclear reactor into light so-called sterile neutrinos. It is located at the Institut Laue–Langevin in Grenoble, France.
Karlsruhe Institute for Technology	Karlsruhe Tritium Neutrino Experiment (KATRIN) measures the neutrino mass via ultrahigh precision measurements of the kinematics of electrons from beta-decay. KATRIN started beta-decay data taking officially in spring 2019.[105]

5.0 High Performance Scintillators, Cherenkov Materials and Other Optical Components

High performance scintillator materials are needed for particle identification and measurements of energy and momentum of electromagnetic particles in modern nuclear physics experiments. This includes scintillator and Cherenkov materials for detecting and counting photons and charged particles over a wide range of energies (from a few keV to up to many GeV). These include crystalline, ceramic, glass, and liquid scintillators (both organic and cryogenic noble liquids) for measuring electromagnetic properties (e.g., for high resolution EM calorimetry) as well as for particle identification. The majority of these detectors e.g., calorimeters, require large area coverage and therefore cost-effective methods for producing the materials are required. Examples include:

- **Non-hygroscopic scintillating crystals with high light output and fast decay times**
- **Radiation resistant scintillating fiber assemblies for beam tracking of rare isotope beams**
- **Radiation resistant fast scintillators with timing resolution better than 100 ps.**

Scintillators are used in high energy physics experiments and astrophysics. Industrial applications include geophysical exploration, radiation monitoring, process control and thickness gauging, metallurgical and spark analysis, container scanning, mineral processing, analysis in coal processing, and oil well logging, among others.[106]

5.1. Potential Applications

Radiation-hardened scintillators will be used for calorimeter detectors in nuclear physics experiments at research institutions and universities. In addition, these scintillators have the potential to be used with commercial radiation detection applications in military and homeland security. For example, the Department of Homeland Security needs to be able to distinguish between neutrons and gamma rays. Scintillator and Cherenkov materials could significantly reduce the false alarm rate in passive nuclear detection systems and allow for large range of deployment; security applications as active material for radiation portal monitors such as at ports where cargo screening. Potential medical applications include anything that relies on a scintillator – such as a PET scan.

5.2. Other Agencies

Scintillators used in defense and homeland security applications operate in complex environments, very different from those found in traditional counting/spectroscopy laboratories and physics experiments. In the field of homeland security, scintillator crystals used in nuclear security are numerous and varied in scope. Applications include:

- **Search and detection – cargo and people screening**
- **Identification of nuclear materials**
- **Contamination zone mapping**
- **Unattended monitoring**
- **Countering the threat of nuclear materials smuggling; etc.**

5.2.1. Homeland Security – Customs and Border Patrol (CBP)

Radiation portal monitors (RPMs) are used at U.S. land and seaports of entry by CBP to scan cargo and conveyances to prevent the smuggling of Radiological/Nuclear threats or threat materials into the United States. In 2015, DHS released the “Portable Radiation Portal Monitors Market Survey Report”[107] to assist emergency responders making procurement decisions. The Figure below provides a summary of RPMs included in the survey, including specifications. As shown in the Table below, almost all of them did not have spectroscopic or neutron detectors and have on average two plastic scintillators.

Company	Product	Cost ($)	Warranty Period (years)	GSA Schedule	Weight (pounds)	Carrying Case Dimensions (inches)	Wheeled Case	Portal Inside Dimensions (inches)	Battery Type, Life	Detector Quantity and Type	Detector Dimensions (inches)	Total Detection Volume (liters)	Meets FEMA REP-21	Spectroscopic Detectors	Neutron Detectors	Vehicle Monitor Kit
Canberra Industries, Inc.	MiniSentry	NA	NA	NA	108	NA	Opt	30 x 80	Sealed lead acid, 40 hours	2 plastic scintillators	72 x 3 x 1.5	10.6	Yes	NA	NA	Opt
Laurus Systems, Inc.	TPM-903B	13,920	1	Yes GS-07F-0147T	110	80 x 18 x 18	Opt	NA	6 D cells, 40 hours	2 plastic scintillators	72 x 3 x 1.5	10.6	Yes	No	No	Opt
Ludlum Measurements, Inc.	Model 52-1-1 Personnel Portal Monitor	12,041	1	No	100	48 x 24 x 12	Yes	32 x 81	3 D cells, 24 hours	4 plastic scintillators	NA	11.0	Yes	No	No	No
Rapiscan Systems	TSA PM704	12,240	1	No	190	15 x 30 x 83	Yes	NA	8 D cells, 14 hours	2 plastic scintillators	72 x 3 x 1.5	10.6	No *	No	No	No
WB Johnson Instruments	AM-801	11,486	2	Yes GS-07F-0147T	110	50 x 27 x 13	Yes	36 x 84	6 D cells, 18 hours	4 plastic scintillators †	36 x 3 x 1.5	10.6	Yes	No	No	Opt
US Nuclear Corporation	Portable Personnel and Vehicle Monitor	17,700	1	No	128	54 x 16 x 7 per detector, 20 x 16 x 10 control case	Yes	No portal ‡	Recharge able, 10 hours	2 plastic scintillators	44 x 12 x 1.5	12.8	Yes	Opt	Opt	Yes

* This system meets security screening standards ANSI N42.35 and ASTM C-1169.
† Additional plastic scintillators on the top panel and bottom panel are available as an option.
‡ This system contains two detector panels that are 54 inches in height and can be separated between 24 and 240 inches.

Abbreviations:
NA = information not available
Opt = optional feature available at additional cost

Figure 8: Product Matrix for Radiation Portal Monitors
Source: National Urban Security Technology Laboratory[108]

DHS's fleet of almost 1,400 RPMs for scanning incoming cargo and vehicles for radiological and nuclear materials.[109] By August 2016, DHS had 1,386 RPMs deployed—including 277 Ludlum RPMs and 1,109 Leidos RPMs.[110] Some of the RPMs began to reach the end of their estimated 13-year service life. In 2016, DHS changed the focus of its RPM replacement strategy to selective replacement of RPMs—using existing RPMs that have been upgraded with new alarm threshold settings or purchasing enhanced, commercially available RPMs—to gain operational efficiencies. The report noted high nuisance alarms in RPMs:[111]

> Upgrades enable improved threat discrimination and minimizes “nuisance” alarms created by naturally occurring radioactive materials (NORM) in commonly shipped cargo such as ceramics, fertilizers, and granite tile. Improved discrimination

> between NORM and threat material will create efficiencies for the movement of cargo through ports and minimize time that DHS's Customs and Border Protection (CBP) officers spend adjudicating the nuisance alarms. DHS is also planning limited replacement of upgraded RPMs at select high-volume ports with enhanced, commercially available RPMs that offer nuisance alarm levels significantly lower than even the upgraded RPMs. Currently, upgraded RPMs at some high-volume ports do not reduce nuisance alarm rates enough to implement remote RPM operations—which allows CBP officers to carry out other duties at the ports when not responding to an RPM alarm—because of the high number of vehicles and cargo containers passing through the ports daily.[112]

The Countering Weapons of Mass Destruction Office (CWMD) acquires and deploys nuclear, radiological, chemical, and biological systems to support Department of Homeland Security operational components such as U.S. Customs and Border Protection and U.S. Coast Guard.[113] As part of its charter, CWMD is responsible for purchasing RPMs.[114]

In the FY2025 Budget, the CWMD RPM program planning and budget justifications (written explanation for the amount an agency requests for its annual operating budget) includes funding required to complete deployment and installation of replacement of RPMs at seven points of entry and decommission 10 RPMs. "The current RPM fleet is obsolete and substantially past its life expectancy. The systems have several known technical limitations that cannot be fixed."[115] The budget justification lists the following vendors, that are also potential partners to companies seeking to enter this space:

- **Leidos**
- **Smiths Detection**[116]

CWMD also supports the procurement of chemical, biological, and radiological detection equipment that can be carried, worn, or easily moved to support operational end-users:

- **Personal Radiation Detectors** are pager-size devices always worn by an operator for the purposes of R/N detection.
- **Contractors**: Polimaster, Inc., Thermo-Fisher, William F. Hawk Consulting, Inc.
- **Basic Handheld Radioisotope Identification** devices are used for search, detection, localization, and identification of R/N materials, and for quick and accurate measurement of dose rate and count rate.
- **Contractor**: Symetrica, Inc

- **Multi-Modal Sensors** combine chemical, biological, and/or radiological detectors into single portable monitoring systems to enhance operational user capabilities and address multiple threats.[118]

Table 6: Countering Weapons of Mass Destruction Office

Government	Countering Weapons of Mass Destruction Office
Industry	L-3Harris Leidos Smiths Detection Polimaster, Inc. Thermo-Fisher Scientific, Inc. William F. Hawk Consulting, Inc. Symetrica, Inc.

Cargo screening will allow for the rapid detection of both neutrons and gamma rays. An issue in cargo portals is that the port owners want real time detection. That is that the cargo container goes through the portal at standard speed. Within DHS, cargo screening is the responsibility of

1. **The Container Security Initiative (CSI)** allows U.S. Customs and Border Protection (CBP), working with host government Customs Services, to examine high-risk maritime containerized cargo at foreign seaports before they are loaded on board vessels destined for the United States.[117]

2. The **Transportation Security Administration** is responsible for ensuring the security of all modes of transportation, including cargo placed aboard airplanes and particularly focuses on passenger-carrying planes.[118] Air cargo includes property tendered for air transportation accounted for on an air waybill. All accompanied commercial courier consignments, whether accounted for on an air waybill, are also classified as cargo. The air cargo operations serving the United States are made up of over 300 domestic and foreign air carriers, and over 4,000 indirect air carriers.[119] There are approximately 440 airports in the United States that have airport security programs under the responsibility of TSA.[120]

Table 7: Potential Partners in the U.S. – Homeland Security

Activities and Potential Partners in the U.S. – Homeland Security	
Government	TSA U.S. Customs and Border Protection Countering Weapons of Mass Destruction DHS Science & Technology

5.2.2. National Aeronautics and Space Administration (NASA)

Advanced scintillators and readout devices for high-energy astronomy for NASA is another potential opportunity. Scintillator based high energy X-ray and Gamma Ray detectors are finding increasing applications in astrophysics, earth science, heliophysics, and planetary science. Scintillators are the "eyes" of the high energy photon and particle detection systems, and its qualities directly affect the detector performance. The identification and development of heavy, fast, robust, bright and efficient scintillation crystals will greatly benefit the future generations of NASA detectors for its various missions.

NASA is developing and advancing detector technologies focused on UV, x-ray, and gamma ray spectral ranges.[121] NASA requirements across the board are for greater numbers of readout pixels, lower power, faster readout rates, greater quantum efficiency, single photon counting, and enhanced energy resolution.[122] Current NASA missions under considered in NASA's [2020 Astrophysics Decadal Studies](), include various programs such as Future UV/Optical and Exoplanet missions (Habitable Exoplanet Observatory (HabEx) or Large Ultraviolet Optical Infrared Surveyor (LUVOIR)), LYNX and the Origins Space Telescope Study.

- LUVOIR- Large UV/Optical/IR Surveyor: https://asd.gsfc.nasa.gov/luvoir/
- Habitable Exoplanet Observatory (HabEx): https://www.jpl.nasa.gov/habex/
- The LYNX Mission Concept: https://wwwastro.msfc.nasa.gov/lynx/
- NASA Astrophysics: https://science.nasa.gov/astrophysics/
- The Explorers Program: https://explorers.gsfc.nasa.gov/

NASA is also investigating readout electronics, "The future of long-wave detectors is moving toward tens of thousands of pixels and beyond. Readout circuits capable of addressing their needs do not exist, and without them the astronomical community will not be able to keep up with the needs of the future." Sample NASA programs where their readout electronics are need include science missions utilizing 2D, large-format cryogenic readout circuits such as:

1. HAWC + (High Resolution Airborne Wideband Camera Upgrade) for SOFIA (Stratospheric Observatory for Infrared Astronomy)
2. PIPER (Primordial Inflation Polarization Experiment), balloon-borne.
3. PICO (Probe of Inflation and Cosmic Origins), a probe-class cosmic microwave background mission concept.[123]

The **"Vision and Voyages for Planetary Science in the Decade 2013-2022"**, calls for the development of "low mass and low-power electronics, as well as high-resolution and high-sensitivity instruments, are necessary in many applications including ground-based instrumentation; support that is directed to instrument programs that support these areas of development will be particularly beneficial."[124]

In addition, observations at energies above ~10 keV include:

- Hard X-ray/Soft Gamma-Ray Band (10 – 600 keV)[125]
- Medium-Energy Gamma-Ray Band (0.5 – 20 MeV) such as the All-sky Medium Energy Gamma-ray Observatory (AMEGO)[126]

5.3. Academic and Other Research Institutions

Radiation-hard scintillators calorimeter detectors are also used in nuclear physics experiments at research institutions and universities. The Table below lists design parameters for some crystal calorimeters built for high-energy physics (HEP) experiments.

Table 9: Calorimeter Detectors

Experiment	Lab
Compact Muon Solenoid (CMS)	The Compact Muon Solenoid is a general-purpose detector at the Large Hadron Collider. It has a broad physics program ranging from studying the Standard Model (including the Higgs boson) to searching for extra dimensions and particles that could make up dark matter.[127]
Large Hadron Collider (LHC)	LHC was built by the European Organization for Nuclear Research (CERN) between 18 and 2008 in collaboration with over 10,000 scientists and hundreds of universities and laboratories, as well as more than 100 countries.[128]
ATLAS (A Toroidal LHC ApparatuS)	The ATLAS experiment ("A Toroidal LHC Apparatus") detects the subatomic particles created after beams of particles smash into each other at near light speed at the LHC, which is operated by the European Organization for Nuclear Research (CERN).[129]
C-BARREL	The CERN CMS electromagnetic calorimeter is a homogeneous calorimeter made of 75 848 lead tungstate ($PbWO_4$) scintillating crystals, located inside the CMS superconducting solenoid magnet.[130]

The search and development of scintillators has been for a long time mainly focusing on improving the light yield and energy proportionality response to improve the energy resolution, a new trend for fast timing capability has recently emerged.[131] This requirement is mainly driven by HEP experiments and TOF-PET applications.

X-ray free electron lasers (XFELs), such as could make use of high-speed imaging technologies made possible by advances in scintillator materials. The Table below provides a listing of XFELs in the world.

Table 10: X-ray Free Electron Lasers (XFEL)

XFEL	Location
Linac Coherent Light Source (LCLS)	The LCLS, located at the SLAC National Accelerator Laboratory, began operations in 2009 and was the first facility in the world to lase in the hard X-ray range.[132]
European XFEL	The European XFEL is located between the states of Hamburg and Schleswig-Holstein, Germany. user operation began in September 2017.[133]
SACLA	The SACLA XFEL is located in Hyogo, Japan, and began operation in 2012. It is driven by a normal conducting linac, currently operating at a maximum repetition rate of 30 Hz.[134]
SwissFEL	The SwissFEL is located at the Paul Scherrer Institute, in Villigen, Switzerland, is at an advanced stage of construction and has already started to lase in 2016. It is driven by a normal conducting linac, with a repetition rate of 100 Hz.[135]
Pohang Accelerator Laboratory (PAL) XFEL	The PAL XFEL is located in Pohang, Korea. PAL-XFEL consists of a Hard X-ray (HX) and a Soft X-ray (SX) FEL line. The HX line includes a 780 m long accelerator line, a 250 m long undulator line, and 80 m long experimental halls. The SX line is branched at 260 m point from beginning. It includes a 170 m long accelerator line, a 130 m long undulator line, and a 30 m long experimental hall. The HX line generates 2~15 keV FEL with over 1 mJ pulse energy, 10~35 fs pulse duration, and under 20 fs arrival time jitter from 4~11 GeV electron beams. The SX line generates 0.25~1.25 keV FEL with over 1012 photons from 3 GeV e-beams.[136]

The successful clinical introduction of novel imaging systems is based on reliable and high-performance detector technology but also requires a clear application and a sufficiently large market. The positron emission tomography/computed tomography (PET/CT) market has exceeded growth expectations over the last few years, chiefly due to superior quantitation accuracy and better imaging compared to SPECT/CT. he global positron emission tomography (PET)/computed tomography (CT) scanner device market size is expected to reach $3.34 billion by 2028.[137]

PET systems have been improved steadily with regard to sensitivity and resolution by optimizing the detectors and geometry (see Figure below).

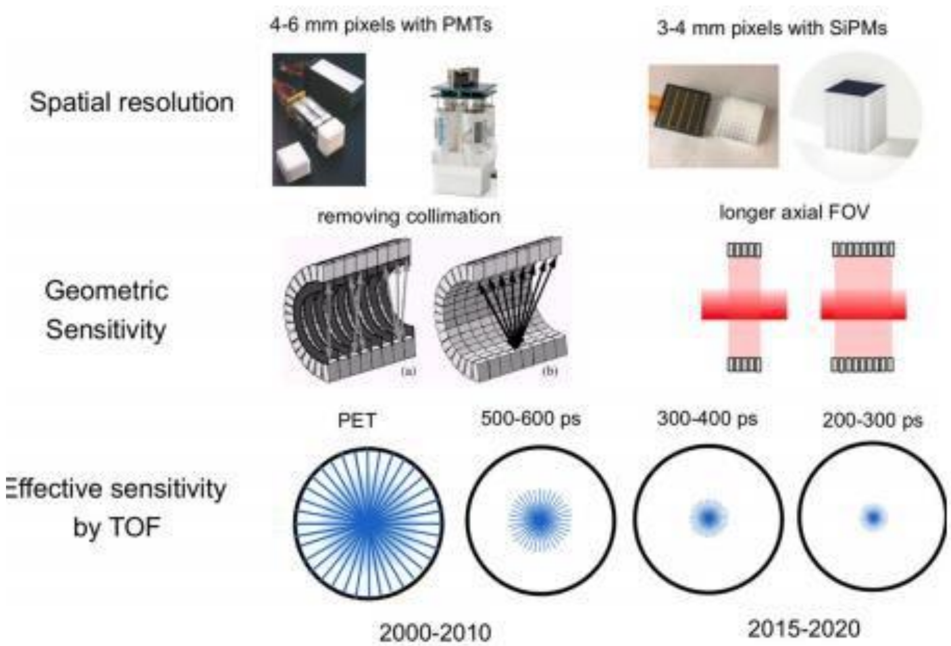


Figure 9: The three major improvements in PET technology during the last three decades
Source: Vandenberghe et al. 2020[138]

Most clinical systems are still based on PMTs. Some recent PET detectors are based on silicon photomultipliers (SiPM), for example,

- Philips Vereos PennPET Explorer utilizes proprietary Digital Photon Counting technology, offering benefits along the imaging chain. The crystal and sensors are coupled one-to-one. The light produced by the crystal are channelized directly on individual digital sensors. The system consists of 23,040 PET detectors with PET quantitative accuracy of +/- 5%.

- The Canon Medical Systems Cartesion Prime PET/CT hybrid system is a digital solution that consists of SiPM photosensors for better image quality, scan times, and dose efficiencies. The system combines the features of Canon's SiPM PET detector and the Aquilion Prime SP CT system. The system offers one-to-one SiPM to Crystal Coupling, 27 cm axial field of view with air cooling technology. The system offers fast TOF resolution for enhanced productivity and high-quality images.[139]

New detector technologies are needed for TOF-PET:

> "A next logical step towards better PET systems is to further increase timing resolution although realizing further major improvements in timing resolution (below 200 ps) will require new detector concepts and it may take about 10 years before such technology is mature enough for introduction in a clinical PET system."[140]

Current PET systems with the TOF resolution (at the system level) include:

- The PennPET Explorer (250 ps) is based on a digital silicon photomultiplier developed by Philips. The configuration has three rings – each consisting of 18 detector modules – and an axial FOV of 64 cm. The scanner has a spatial resolution of 4.0 mm and time-of-flight resolution of 250 ps – leading to state-of- the-art imaging performance.[141]

- Siemens Biograph Vision (214 ps) has a 3.2 mm SiPM detector technology and ToF performance. 100% coverage of the SiPM sensors leads to the fastest time- of-flight to improve contrast and signal-to-noise ratio. Siemens makes the LSO scintillator.[142]

Table 11: Potential Partners – Biomedical Imaging

Potential Partners - Biomedical Imaging	
Government – National Institutes of Health	**National Institute of Biomedical Imaging and Bioengineering (NIBIB):** The Division of Applied Science & Technology supports the development of innovative biomedical imaging technologies.[143] **Nuclear Medicine Program:** NIBIB's Nuclear Medicine program "supports the research and development of technologies and techniques that create images using gamma-ray (SPECT) or positron (PET) emissions from radioactive biological agents that are injected, inhaled, or ingested into the body."[144] **Emphasis:** "Simulation and development of new detectors, collimators, and readout methods that enhance the signal quality of detecting isotope emissions; designs of novel camera geometries; and correction methods that compensate for the radiation physics properties to improve the clinical reliability of the image. Of interest are improvements and corrections for interaction events in PET detectors and enhancement to TOF image generation methods (reconstructions algorithms); as well as new collimator and camera designs for SPECT."[145] **Molecular Probes and Imaging Agents Program:** "This program supports development and biomedical application of molecular probes and imaging agents across all imaging modalities for the visualization, characterization and quantification of normal biological and pathophysiological processes and anatomy in living organisms at the molecular, cellular and organ levels. … The goal of this program is to generate robust molecular probes, imaging agents and platforms for biomedical application across all disease areas to facilitate diagnostics and improve understanding of disease state, progression, and therapeutic response."[146]

Industry Partners	The PET/CT equipment market until recently has been limited to three market participants:[147] • Philips Healthcare • GE Healthcare • Siemens Healthineers AG Siemens Healthineers (Germany), GE Healthcare (U.S.), and Philips Healthcare (Netherlands) are the leading players in this market and together account for approximately 93% of the market share.

5.4. Bolometers

This section provides information on some of the potential programs using bolometers. Bolometers have been subjected for extensive research for years. While bolometers can be used to measure radiation of any frequency, for most wavelength ranges there are other methods of detection that are more sensitive. For sub-millimeter wavelengths, also known as the far-infrared or terahertz), bolometers are among the most sensitive available detectors, and are therefore used for astronomy.[148] Notable examples of bolometers employed in submillimeter astronomy include:

- Herschel Space Observatory (operated by California Institute of Technology)[149]
- James Clerk Maxwell Telescope (operated by East Asia Observatory)[150]
- Stratospheric Observatory for Infrared Astronomy (SOFIA) 80/20 joint project of NASA and the German Aerospace Center.[151]

The term bolometer is also used in particle physics to designate an unconventional particle detector NASA missions with super-cooled telescopes have the potential for orders of magnitude improvement in sensitivity, but detector improvements are needed to fully capitalize on these new platforms. Missions currently under discussion include:

1. European Space Agency and the Japan Aerospace Exploration Agency are considering the Space Infrared Telescope for Cosmology and Astrophysics (SPICA) mission featuring a 2-meter telescope and instruments, which could include US participation to be launched in 2027-2028.[152]
2. NASA has commissioned studies of (a) a 2-meter Galaxy Evolution Probe[153]— and (b) a 5.8-meter, Origins.[154] These two concepts are under consideration by the panels developing the National Academies of Science, Engineering and Medicine's 2020 Astrophysics Decadal Survey.

“Origins” detectors:

> “Detector technology development plan will reach TRL 5 by 2025.
> - Transition-edge Sensor (TES) bolometers: operate <50 mK, for FIP, OSS and MISC-T
> - Kinetic Inductance Detectors (KIDs) operate <50 mK, for FIP, OSS
> - Si: As arrays: operate 7 K, high stability for MISC-T
> - HgCdTe arrays: operate 30 K, high stability for MISC-T.”[155]

Table 12: NASA – Potential Programs for Bolometers

Program	Description
Bolometers for Origins program	The Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration team is developing superconducting transition-edge-sensed bolometers that both meet the Origins sensitivity requirement and use this readout approach.
Galaxy Evolution Probe	University of Colorado, Boulder
NASA sponsoring organization	Astrophysics Division’s Cosmic Origins and Strategic Astrophysics and several international flight missions under development.

Bolometer Market

A bolometer is a type of sensor used to measure electromagnetic radiation's power in the infrared, microwave, and radio frequency range. The global bolometer market is projected to grow from $1.02 billion in 2017 to $2.06 billion by 2030.[156] **A compounded annual growth rate (CAGR) of 7.5% is projected from 2017 to 2030**. Some of the key companies producing balometers and microbolometer arrays include BAE Systems, RTX, Teledyne Dalsa and FLIR, L-3Harris, Honeywell, Leonardo DRS among others.[157]

There are several types of bolometers including microbolometer and hot-electron bolometer. Microbolometer is an uncooled infrared detector that converts infrared radiation into a visible image. The global market for microbolometers had a market value of $91 million in 2022 and is projected to reach $130 million by 2028. MarketsandMarkets project a CAGR of 6.6% from 2023 to 2028. These detectors are used in various applications such as surveillance and security, spectroscopy and temperature measurement.

Table 13: Global Microbolometer Market, By Application, 2023–2028 ($M)

Application	2023	2024	2025	2026	2027	2028	CAGR (2023–2028)
People & Motion Sensing	35.82	38.02	40.52	43.30	46.36	49.72	6.8%
Temperature Measurement	14.41	15.20	16.10	17.09	18.17	19.37	6.1%
Security & Surveillance	26.89	28.70	30.75	33.04	35.57	38.36	7.4%
Gas & Fire Detection	8.25	8.67	9.15	9.69	10.26	10.89	5.7%
Spectroscopy & Biomedical Imaging	7.61	7.95	8.34	8.77	9.23	9.73	5.1%
Others	1.80	1.88	1.96	2.05	2.17	2.29	4.9%
Total	**94.77**	**100.43**	**106.83**	**113.95**	**121.77**	**130.36**	**6.6%**

Source: MarketsandMarkets. "Infrared Detector Market – Global Forecast to 2028." (June 2023)[158]
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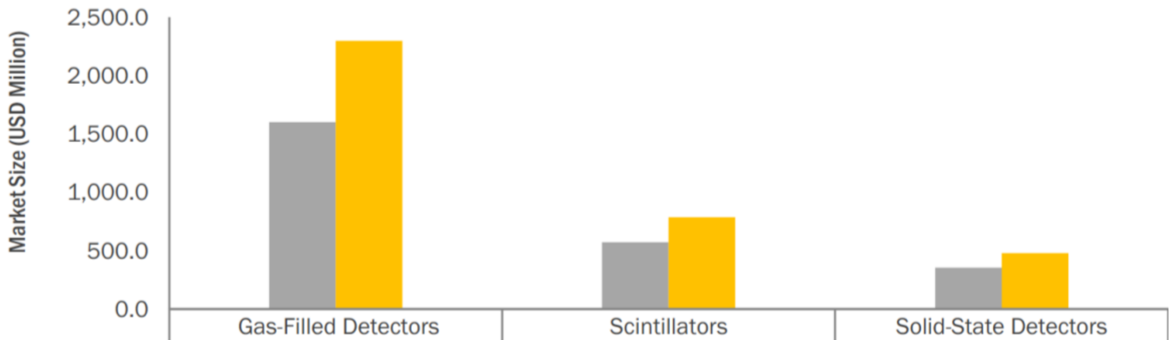
Some of the key companies producing microbolometer include BAE Systems, RTX, Teledyne Dalsa and FLIR, Lynred, Leonardo DRS among others[159]

Scintillator Materials Market

Scintillators, with the ability to convert ionizing radiation into visible photons, have received extensive attention in recent years. Scintillator **materials are currently widely used in many detection systems addressing different fields such as** radiation detectors for radiation exposure monitoring, security inspection, space exploration, and medical imaging, high energy physics, calorimetry, industrial control, and oil drilling exploration. Various types of materials have been used for X-ray scintillators, there are still many issues and limitations.[160]

Scintillator market applications are largely dependent on the composition of the scintillation materials, since by modifying the scintillator composition or adding external activator, the desired application can be achieved. Scintillators can be classified into two types: (1) organic; and (2) inorganic. Inorganic scintillators dominate the scintillator material market; however, new innovations have resulted in new generation materials comprising doped and oxide based inorganic crystals. Plastic scintillators are the most commonly used organic scintillators for large area detection, due to their production in large units and the low cost associated with their fabrication. MarketsandMarkets forecasts the global radiation detection scintillators market to reach almost $787 million in 2027, from $571 million in 2022. (Figure 10)

The majority of the market is expected to remain gas-filled detectors (i.e., Geiger counters), with scintillator and solid-state detectors making up the balance. The gas-filled detectors segment accounted for the largest share of 63% of the global market in 2022. This segment is projected to reach $2.3 billion in 2027 from approximately $1.6 billion in 2022. Key drivers include safety concerns, new and improved scintillators for medical devices, homeland security operations, and a shortage of neutron detection materials.[161]



	Gas-Filled Detectors	Scintillators	Solid-State Detectors
2022	1,599.8	571.0	355.3
2027	2,296.1	787.2	479.6
CAGR	7.5%	6.6%	6.2%

Figure 10: Global Radiation Detection Market – Composition
Source: MarketsandMarkets, February 2023[162]
Reprinted with permission from MarketsandMarkets

Inorganic scintillator materials and detectors are manufactured by many market players including Saint Gobain (U.S.), Rexon Components Inc. (U.S.), Scionix (U.K.), Argus Imaging (Netherlands), Canberra industries (U.S.), Ludlum (U.S.), and Toshiba Materials (Japan), among others. Inorganic scintillator materials manufacturers include Eljen Technology (U.S.), Saint Gobain (U.S.), EPIC Crystal (China), Berkeley Nucleonics Corporation (U.S.), and Rexon Components (U.S.).[163]

6.0 Technology for High Radiation Environments

Next generation rare isotope beam facilities require new and improved techniques, instrumentation, and strategies to deal with the anticipated high radiation environment in the production, stripping and transport of ion beams. DOE is looking to support the development of tools to convert 3D-CAD geometries into geometry models that can be used in common radiation transport codes like Mars, PHITS, MCNPx and others and advanced visualization and analysis tools of radiation transport calculation results and for these geometries.

The most common radioisotope used in diagnosis is technetium-99 (Tc-99), with some

40 million procedures per year, accounting for about 80% of all nuclear medicine procedures and 85% of diagnostic scans in nuclear medicine worldwide. The main world isotope suppliers are Curium (France and USA), MDS Nordion (Canada), IRE (Europe), NTP (South Africa), Isotop-NIIAR (Russia), and ANM (ANSTO Australia). Most medical radioisotopes made in nuclear reactors are sourced from relatively few research reactors, which are all outside of the United States.[164] Within the United States, in 2019 the Department of Energy's National Nuclear Security Administration (NNSA) awarded $15 million in matching funds to three companies to develop a domestic supply of molybdenum-99 without the use of highly enriched uranium (HEU):

- NorthStar Medical Radioisotopes, LLC (Beloit, Wisconsin)
- SHINE Medical Technologies (Janesville, Wisconsin)
- Niowave, Inc. (Lansing, Michigan)[165]

6.1. Other Agencies

6.1.1. NASA - Simulation for High Radiation Environments

NASA plans for a sustainable return to the moon, astronauts will once again leave Earth's protective magnetosphere only to endure higher levels of radiation from galactic cosmic radiation and the possibility of a large solar particle event. NASA has initiated multiple programs to help the agency achieve its Artemis mission and longer-term lunar exploration goals.[166] These programs include: 1) a platform in the lunar orbit; 2) a landing system to put humans on the surface of the Moon; and 3) robotic lunar landing services. Gateways, lunar landers, and surface habitats will be designed to protect crew against solar particle events with vehicle optimization, storm shelter concepts, and/or active dosimetry.

Table 15: NASA – NASA Space Radiation Laboratory

Program	Description
NASA Space Radiation Laboratory (Upton, NY)	Jointly managed by the U.S. Department of Energy's Office of Science and NASA's Johnson Space Center, the facility employs beams of heavy ions that simulate the cosmic rays found in space. The Lab helps to assess health risks of cosmic radiation. To better understand these risks.[167]

6.2. Other Applications

Radiotherapy treatment modalities such as external beam radiotherapy (EBRT), internal beam radiotherapy/brachytherapy (IBRT), and systemic radiotherapy products have been gaining in importance in recent years. Technological advancements in radiotherapy and the rising incidence of cancer are the major factors driving the growth of this market.[168] Use of an accurate dose calculation is important. Examples of dosage treatment planning systems include:

- Varian for the Eclipse treatment planning system (Varian Medical Systems, Palo Alto, CA).

Table 16: Radiotherapy

Potential Partners in the U.S.	
National Institutes of Health	National Cancer Institute: The Radiation Research Program (RRP) is responsible for the management of NCI's support for research across the radiation sciences spanning clinical trials, combined modality radiotherapy, experimental therapeutics, radiation treatment planning, radiobiology, physics, and technology.[169]

Industry (U.S. companies)	The dominant players in the global radiotherapy market include: • Varian Medical Systems, Inc. (Siemens Healthineers AG (Germany) acquired Varian Medical Systems, Inc. in April 2021) • Elekta (Sweden) • Accuray Incorporated (U.S.) • Ion Beam Applications SA (Belgium) Eckert & Ziegler (Germany) • Hitachi Ltd. (Japan) ICAD, Inc. (U.S.) • IntraOp Medical, Inc. (U.S.) IsoRay Medical, Inc. (U.S.) • Mevion Medical Systems, Inc. (U.S.) • Panacea Medical Technologies Pvt. Ltd. (India) P-cure Ltd. (Israel) • ViewRay, Inc. (U.S.) ZEISS Group (Germany)[170] Varian Medical Systems (U.S.) is one of the leading players in the global radiotherapy market. Its broad portfolio of radiotherapy systems and brachytherapy products is the key factor accounting for its large share in this market. The company is focused on organic strategies such as product launches and introduced several new and advanced radiotherapy systems and received regulatory approvals for products in the past three years, such as the ProBeam 360 single-room proton therapy system, ProBeam 360 with multi-room configuration, Halcyon 2.0 system, and Calypso Anchored beam transponder system for linacs, among others.

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