U.S. DEPARTMENT OF ENERGY | Office of Science

Workshop on Energy and Environmental Applications of Accelerators

June 24–26, 2015

Cover Photo of cityscape: Reidar Hahn

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Executive Summary

Particle accelerators are not only powerful tools for discovery science, but also essential tools in industry, medicine, and national security. Recent advances in particle accelerator technology have the potential to benefit many energy and environmental (E&E) applications, such as:

- Treating potable water, waste water, and sludge,
- Removing pollutants from stack gases,
- Treating medical waste,
- Conducting environmental remediation of hydrocarbon contaminated soil and conversion of fossil fuels,
- Treating asphalt to improve wear resistance,
- Increasing the capacity of wind generators,
- Enhancing the magnetic separation of material streams, and
- Increasing the efficiency of electrical power transmission.

The U.S. Department of Energy (DOE) Office of High Energy Physics within the Office of Science, as the host office for the Accelerator Stewardship Program, sponsored a basic research needs workshop (June 24–26, 2015, Argonne National Laboratory) to assess the R&D needed to enable high-impact applications of accelerator technology to address E&E challenges. The workshop brought together nearly 40 experts in E&E applications and particle accelerator technology to:

1) Assess the existing accelerator-based technologies currently deployed for E&E applications,
2) Develop criteria for accelerator-based systems for each application, and
3) Develop a set of R&D thrusts needed to bridge technical gaps associated with the application of accelerator technology to E&E challenges.

The technologies that support E&E applications must operate in a complex environment with many government regulations and industrial constraints. Both the performance and economic competitiveness of new E&E technologies will be critical for their successful adoption. In addition to these factors, other forces are at work, including the regulatory landscape, public perception of new technologies, and market incumbency of previous technologies. Therefore, one of the major goals of the workshop was to document in detail a complete picture of the landscape for potential applications of accelerator technology.

The basic impediments to deployment of accelerator-related technology are as follows: i) lack of availability of accelerator systems that meet the required performance levels for full-scale industrial application, which are typically a factor of ten or more beyond today's state of the art, ii) the need for accelerator systems that are both highly efficient and reliable, yet economically competitive with incumbent technologies, and iii) lack of pilot-scale applications of these new technologies to demonstrate their efficacy and performance.

A broad spectrum of research needs was identified that would allow electron beam and superconducting technologies to be advanced from an innovative technology to one that is truly disruptive in the E&E marketplace. Because of the broad scope of applications considered and the diversity of the workshop attendees, the resultant list of research needs was wide ranging. The identified research needs were refined and prioritized in terms of a) immediate (near-term) science-based research needs and b) synergistic and applied research (longer term). These research needs are described in detail in the report. Some of the important near-term science-based research needs include:

1) Developing concurrently the application-side science as the accelerator technology advances; this will be key to realizing the promise of E&E applications,
2) Advancing accelerator R&D on very high-power electron beam generation, acceleration, and transmission,
3) Engineering electron beam technologies with increased efficiency and reliability, as well as lower cost per delivered watt of beam power,
4) Developing science-based predictive models to understand radical yield from irradiated aqueous systems as modified by environmental parameters,
5) Advancing R&D to understand the chemistry of electron beam irradiation of hydrocarbons in the environment,
6) Advancing R&D to understand the operation of high-temperature superconducting coils in the temperature and current ranges relevant for industrial applications,
7) Demonstrating cryogen-free systems for magnets and accelerators, and
8) Developing an understanding of superconductor performance and properties above 4 K.

In addition to identifying the research needs listed above, the workshop attendees also projected that progress in the basic research described in this report stands to benefit, in particular, applications in domestic sewage sludge detoxification, medical waste sterilization, flue-gas treatment for air-borne contaminants, and industrial waste treatment. For these applications, electron beam technology has the potential to quickly become disruptive in the marketplace.

1. Introduction

1.1 Motivation for the Workshop

Particle accelerators are not only powerful tools for discovery science, but also essential tools in industry, medicine, and national security. At the same time, particle accelerator technology advances of the last few decades now have the potential to benefit technology for energy and the environment. To that end, the Office of High Energy Physics, as the Department of Energy's (DOE's) host office for the Accelerator Stewardship Program, has conducted a basic research needs (BRN) workshop (June 24–26, 2015 held at Argonne National Laboratory) to assess R&D needed to enable high-impact applications of accelerator technology to address energy and environmental (E&E) challenges. Earlier community input identified the following technology areas as having promise: (1) for near-term impact (<5 year), accelerator-related technologies for efficient manufacturing and superconducting generators, and (2) for medium-term impact (<10 years), medium- and high-power, low-energy, electron beam accelerators.

Present and proposed uses for accelerator technology in E&E applications include:

- treating potable and waste water,
- treating sludge,
- removing pollutants from stack gases,
- increasing the energy efficiency of industrial material processing,
- increasing the capacity of wind generators,
- enhancing magnetic separation of material streams, and
- replacing radioactive sources in sterilization and environmental monitoring applications.

In many cases, the use of accelerator technology for these applications has performance advantages. However, the barriers to significant commercial deployment of accelerator technology include cost, wall plug efficiency, reliability, regulatory approval, and end user resistance to the risk inherent in changing technology. Many of these E&E needs are currently met by existing, well proven technologies; however, recent improvements in accelerator technology have enhanced the performance, lowered the cost, and increased the reliability of accelerators for E&E applications.

This BRN workshop identified opportunities and barriers to market adoption in the two technology areas noted above. The goal is to identify accelerator technology R&D opportunities that, if pursued, could enable high-impact solutions for current E&E challenges.

1.2 Community Input

This "Workshop on Energy and Environmental Applications of Accelerators" is the culmination of a multi-year community-based activity to assess the potential of particle accelerator technology for solving important societal problems beyond discovery science. In October 2009, DOE's Office of High Energy Physics sponsored a symposium and workshop entitled "Accelerators for America's Future." The purpose of that Workshop, chaired by Walter Henning and Charles Shank, was to elicit the views and opinions of a wide range of accelerator users on the challenges and opportunities for developing and deploying accelerators to meet national needs. The report of this workshop [1-1], published in June 2010, has drawn congressional interest in enhancing U.S. stewardship of accelerator science R&D.

In 2011 DOE's Office of High Energy Physics sought input from the community via the "Accelerator R&D Task Force" on the best strategy for an accelerator stewardship program [1-2]. The program was authorized by Congress in 2014. To assess the potential for interest in accelerator applications in energy and the environment, an RFI was issued in 2014, culminating in 29 responses from practitioners in industry, national laboratories, and universities [1-3].

This BRN Workshop is intended to assess those opportunities and provide information on the challenges—technical, regulatory, and financial—in deploying accelerator technology in E&E applications.

1.3 Workshop Charge

The RFI resulted in the identification of several E&E application areas, some well-known and others emerging. The charge for this BRN workshop is as follows:

1. Assess the state of any existing accelerator and non-accelerator based technology currently deployed for the application. Document cost and performance criteria to be used as a baseline for alternatives utilizing accelerator-based technology.
2. Document current and proposed Federal and State environment, safety, and health regulations for the application and identify any issues with regard to these regulations.
3. Develop criteria for accelerator-based systems for the application. Consider total system costs for production and operation. Assess the potential financial and/or environmental impacts if the accelerator technology meets the criteria. Document specifications for the accelerator component of the system.
4. Identify technical gaps between the current state of the art in accelerator technology compared to the above specifications. This may include accelerator-related technologies such as power supplies or magnet technology.
5. Identify synergistic application-side R&D relevant to the application of accelerator technology to E&E challenges.
6. Specify R&D activities needed to bridge technical gaps, as well as any environmental analysis and testing required to approve their use.
7. Develop a list of R&D and regulatory compliance issues, and calculate first-order funding estimates.

This report represents the output from the workshop. It describes opportunities for accelerator technology to meet E&E challenges and the accelerator R&D needed to address these challenges.

1.4 Applications of Accelerator Technology in Energy and the Environment

The applications under consideration, along with the division of the topic areas in working groups, are summarized in Table 1-1. They fall into two broad categories: applications of electron beams ("e-beams") and applications of superconducting systems.

Table 1-1 Application areas in energy and environment considered in this BRN workshop

Applications of Electron Beam Technology		**Working Group**
Treatment of water and wastewater	Radiation processing to purify and decontaminate water	1
Treatment of flue gas	Radiation processing to purify gas streams	1
Treatment of sewage sludge	Radiation processing to decontaminate sewage sludge	2
Environmental remediation of hydrocarbon contaminated soils	Radiation processing of hydrocarbons to make contaminated soil more amenable to other remediation techniques	2
Medical waste sterilization	Radiation processing to decontaminate medical waste	2
Conversion of fossil fuels	Conversion of fossil fuels by radiation processing	2
Asphalt treatment	Improving wear-resistance and weather-resistance of asphalt via irradiation	2
Applications of Superconducting Systems		
Superconducting wind generators	More compact and efficient wind generators through use of superconductors	3
Magnetic separation	Separation in industrial flow streams with high magnetic fields	3
Electrical grid technologies	Superconducting power transmission and load-leveling	3

1.5 Conclusion

Technologies in areas related to energy and the environment operate in a complex environment with many constraints and forces at work. Clearly, the performance of a new E&E technology as well as its economic competitiveness is central. But no less important are the other forces at work in this complex environment, including the regulatory landscape, public perception of new technologies, and market incumbency of previous technologies. Therefore, a central goal of this BRN workshop is to document a complete picture of the landscape for potential applications utilizing accelerator technology. For a summary of the findings, see Section 4.

2. Applications of Electron Beam Technology in Energy and the Environment

2.1 Environmental Applications of Radiation Processing

Radiation has been utilized in industrial processes for over 50 years. It is now commonly applied in the manufacture of tires, cable, plastic films, and many other products that require polymer cross-linking. The utilization of radiation (accelerated electrons) for environmental applications has been explored over the past 35 years. In that time, a significant amount of research, both university-based and industry-wide, has been undertaken, mostly with positive results. The utilization of radiation has proven effective for sterilization and decontamination of wastewater and sludge and for decontamination of gas streams. However, this technology has not been able to gain acceptance within the environmental field, and it is still considered to be an expensive novelty rather than a serious competitor to other methods of water, gas, and wastewater treatment. One of the major reasons this technology has not been able to grow in the environmental arena is that environmental engineers and scientists are not familiar with the use of radiation as a treatment technology, as there are few demonstration facilities worldwide. Another reason is the lack of high-power, robust, electron beam equipment that can operate continuously in harsh environments.

More recently, within the past 15 years, radiation processes have also been used for environmental applications; pathogen decontamination in foods, pet foods, and food ingredients; and treatment of fruits and vegetables for eliminating insects and pests. While more than 1,500 industrial radiators (not counting medical irradiators) are currently operating world-wide, growth of this technology has been relatively slow. An extensive literature has discussed why the growth of this technology has been slow, suggesting such reasons as aversion to radiation in general by the public, the high cost of utilizing this technology, and the inability of the equipment manufacturers to cooperate among themselves to grow the industry.

Radiation "technology" can be separated into two distinct groups. One is the radiation generated from naturally occurring materials, such as cobalt and cesium (principally gamma radiation). A second group produces radiation utilizing electricity, such as electron beams, or X-radiation also generated from electron beams. These two forms of radiation energy have been compared for different applications in terms of cost, safety, reliability, and the physical characteristics of the radiation produced. Early literature about these topics generally concluded that applications requiring large amounts of radiation energy would be better off utilizing electron beams or X-radiation. Smaller-scale applications would find that gamma radiation from either cobalt or cesium was a more cost-effective approach. However, these arguments turned out to have little practical value, as the licensing restrictions associated with obtaining, maintaining, and disposing of radioactive material such as cobalt or cesium essentially prohibit the large-scale use of these materials. Currently, more than 90% of the industrial radiation equipment utilized world-wide is electron-beam based.

This section will attempt to summarize past work undertaken to evaluate radiation effects on contaminants in aqueous systems and to describe previous attempts to commercialize the technology. The radiation chemistry of aqueous solutions will be described, as will the effects of irradiating water with electrons for contaminant removal. Finally, this section will present future needs in order for this technology to become a valuable treatment alternative for contaminated steams of gas, water, and sludge.

2.1.1 Radiation Chemistry of Aqueous Solutions

Most (if not all) environmental applications involve waste streams that contain liquid water. Exposure of water to high-energy electron radiation (in the MeV range) causes ionization reactions and the generation of free radicals and electrons:

$$e^- + H_2O \rightarrow [2.6]\ e^-_{aq} + [0.6]\ HX + [2.7]\ XOH + [0.7]\ H_2O_2 + [2.6]\ H_3O + [0.45]\ H_2 \qquad (1)$$

The yield of each radical and molecular product per unit energy input has been studied extensively and depends on several factors (pH, dose rate, presence of scavengers, etc.). Aqueous solutions of normal pH (5–11) yield equal amounts of the hydroxyl radical (powerful oxidant) and the aqueous electron (powerful reductant). These reactants cause oxidation and/or reduction reactions to occur in a fraction of a second; therefore, "reaction times" for this process are considered to be essentially instantaneous.

Table 2-1 compares reaction rate constants of ozone (a powerful oxidant) with the hydroxyl radical for a broad range of organic compounds. It can be seen that the reaction rates (oxidation) for the hydroxyl radical are 6–10 orders of magnitude higher than those for ozone. This demonstrates the high reactivity that free radicals exhibit with organic molecules. Also, as was noted above, electron irradiation of water yields an equal amount of solvated electrons (e^-_{aq}) that react with halogenated organics at similar rates.

Table 2-1 Reaction rate constants ($M^{-1}s^{-1}$) for ozone and hydroxyl radicals.

Compound	O_3	OH
Chlorinated alkenes	10^3–10^4	10^9–10^{11}
Phenols	10^3	10^9–10^{10}
N-containing organics	10–10^2	10^8–10^{10}
Aromatics	1–10^2	10^8–10^{10}
Ketones	1	10^9–10^{10}
Alcohols	10^{-2}–1	10^8–10^9

A consideration for irradiating material with high-energy electrons is the penetration depth of the electrons (depends on energy of electrons and density of material, as shown in Table 2-2). The material to be irradiated, in this case water, must be presented to the electron beam in such a way that all of the electrons are utilized for the desired radiation chemistry. In addition, only a thin layer of water can be irradiated, making the hydraulic design of a delivery system challenging. As noted above, the accelerating voltage or the kinetic energy available to the electrons is the main driver of penetration into the water. While different types and powers of electron accelerators are commercially available, utilization of energies greater than 10 MeV is typically avoided due to the possibility of inducing radioactivity in certain materials. The accelerating voltage range of machines anticipated for use in aqueous systems is between 0.5 and 5.0 MeV. A typical application might use an accelerating voltage of approximately 1 MeV, and the range of the accelerated electrons in air from that voltage would be approximately 400 cm. The range of 1 MeV electrons in water, however, is only 0.4 cm. The short penetration in water is accommodated by designing the water delivery system to provide high flow rates in very thin geometries to enable treatment of large volumes. Therefore, design of water delivery systems for electron beam irradiation is a critical component for the design of this equipment for environmental applications.

In summary, the irradiation of water (or moist stack gases) with high-energy electrons will generate large yields of chemically reactive molecules, ions, and free radicals due to the reaction of the electrons with water molecules. Therefore, this technology offers the ability to generate powerful water and wastewater treatment compounds simply by depositing energy in the water. It is obvious that this technology represents a major paradigm shift in ionizing treatment efficiency associated with water, wastewater, and gas treatment. No chemicals of any kind are required; therefore, there will be no increase in total suspended or dissolved solids of the treated water.

Table 2-2 Penetration of electrons vs. accelerating energy.

Electron Energy (MeV)	**Max. range in air (m) (20°C, 1atm)**	**Maximum range in water (mm)**	**Maximum range in Al (mm)**	**Maximum range in lead (mm)**
30	109	132	53.8	10.2
10	43.1	49.8	21.7	5.42
1	4.08	4.37	2.05	0.69
0.1	0.13	0.14	0.069	0.027
0.01	0.0024	0.025	0.0013	0.00073

2.1.2 Introduction to Accelerator Technology

The first electron beams created in the United States occurred in 1926 when a U.S. patent was issued for the production of high-voltage cathode rays outside of the generating tube. Work on electron accelerators continued for the next 30 years, and by 1960 large-scale commercial electron beam accelerators were available in the U.S. market. Since that time, many different geometries of the equipment have been developed and utilized in different commercial settings around the world. The focus of commercial machines, however, is the beam power, as that determines throughput of the product. High-current electron accelerators were developed in the 1960s and have progressed in capacity right up to today. This classic architecture of high current equipment utilizes a transformer to generate the required voltage for accelerating the electrons, as well as an accelerator tube, across which the high voltage is applied. A simple cathode at one end of the accelerator generates electrons, which are then accelerated under high voltage up to an energy level such that the electrons will pass through a thin window containing the vacuum at the end of the accelerator.

Accelerators based on electron beam acceleration in radio-frequency fields are also ubiquitous. These include the linear accelerator and other geometries (see Section 2.11 below). Commercial beams now can be manufactured with energies up to 10 MeV and power levels up to 700 kW. Conversely, smaller self-shielded electron accelerators are now being manufactured commercially for smaller scale applications. These machines usually have accelerating voltages less than 0.7 MeV, and a power range of between 50 and 200 kW.

2.1.3 Large-Scale Environmental Application of Electron Beams

The most obvious and over-arching parameter affecting any environmental treatment technology is its ability to actually achieve desired levels of treatment. In the case of electron beam irradiation of water, sludge, and stack gases, there already is a large database demonstrating its treatment efficacy. Because the chemical process is simple, that is, the generation of free radicals from the interaction of high-energy electrons with a water molecule, the application chemistry is basically that of oxidation or reduction reactions. In fact, any past research utilizing free radicals generated by any process can be informative in terms of treatability efficiency. As noted above, the free radicals generated by any chemistry are the most powerful oxidizing and reducing reactants that can be used in environmental applications.

The volume of literature available on free radical reactions with environmental contaminants is imposing, and clearly demonstrates that laboratory- and/or pilot-scale evaluation of free radicals has already been studied for treatment of most environmental challenges. In fact, the primary design parameter that needs to be determined for this technology is the radiation dose required to generate a sufficient concentration of radicals for the desired treatment. The chemical yield in radiation chemistry is characterized by the G-value. A value of G=1 means that one free radical is formed, or one molecule lost, per 100 eV absorbed energy. The G-value of the hydroxyl radical is 2.8; therefore, 10 kGy will produce 2.8 mM hydroxyl radicals in solution. Because of the large amount of research already published addressing dose requirements for destruction of selected pollutants, good estimates utilizing already available data can be made concerning equipment capacity. This means that the number of treatability studies needed to determine the required dose of electrons for treatment of a specific wastewater is limited. Several review articles on environmental applications are given in Cooper et al. [2-1].

In summary, an enormous literature base exists on the efficacy of utilizing free radicals for treatment of drinking water, wastewater, wastewater sludge, and gas streams. Therefore, a technology capable of generating free radicals, such as electron beams, can have a major impact in the field of environmental protection and contaminant destruction.

The water and wastewater treatment industry is extremely conservative. This industry is responsible for providing treatment on a continuous basis to meet established standards that directly affect the public health of the nation. The introduction of new or innovative technologies to this industry has notoriously been slow, as no one wants to be the first to install unproven treatment systems. While the market for environmental applications is huge, history has shown that successfully penetrating this market is extremely difficult.

Once a new technology has demonstrated its ability to achieve required treatment goals, commercial-grade equipment must then be manufactured to create a treatment facility. Because of the demands on the water and wastewater industry, this equipment must be extremely reliable and available at a reasonable cost. Most new technologies in the area of environmental applications fail at this step in the commercialization process.

Electron beam equipment has been produced commercially for close to 50 years. As noted above, thousands of electron beam accelerators have been manufactured, and most are currently operating in various industries. Therefore, in terms of acceptance in the environmental application industry, the manufacture of commercial-grade equipment should be achievable for small-scale applications. For large-scale applications, a new paradigm is needed, one requiring the development of MW-power-level, compact, highly efficient, cost-effective, and highly reliable accelerators. A challenge will be meeting the very high availability demands required for continuous operation for long periods. This is normally achieved by building redundancy into the design to assure continuous operation even when equipment failures occur. However, this redundancy can also be achieved by redesigning the overall treatment system to include storage capacity, thereby allowing time for the repairs required to bring the equipment back online.

Electron beam equipment is produced commercially all over the world. This means that commercial-grade electron beam accelerators would be available for any installation worldwide. This also means that support and maintenance of this equipment would be readily available worldwide.

Electron beams are one of the most efficient treatment technologies available. Energy (electricity) is transferred directly into the formation of powerful radicals, by simply accelerating electrons that impact water molecules (radiation dose). Radiation dose is described by the unit energy absorbed per unit mass (Gy):

$$1 \text{ Gy} = 100 \text{ rad} = 1 \text{ Joule/ kg} \tag{2}$$

and

$$4.18 \text{ kGy} = 1 \text{ C}^{o} \text{ (temperature rise for 1 kg of pure water)} \tag{3}$$

Therefore, by simply measuring the difference in temperature in a flowing stream before and after irradiation, the total absorbed dose (or degree of treatment) can be estimated.

As an example, a full-scale electron beam system was installed and operated for many years at the Virginia Key Wastewater Treatment Plant in Miami, Florida. The original purpose of the system was to treat digested sludge for land application. Because this system was one of the first installed for this purpose, it was also used for research on the treatment of wastewater effluents, drinking water, and hazardous wastes. This system consisted of a 1.5-MeV, 75-kW high voltage supply coupled with an electron accelerator tube. The electron beam that was generated was scanned out to a window with dimensions of approximately 60 in. x 2 in. The material to be treated was passed through the horizontal beam utilizing a constant flow over a weir. The design parameters were established such that the water fell by gravity through the electron beam, and all of the treatment was achieved in less than one second.

The machine described above was capable of delivering an absorbed dose to the flowing water of approximately 8 kGy or 800 krad. The material to be treated was flowing through the beam at approximately 120 gallons per minute. The data from this full-scale system indicated that 75 kW of beam power can deliver a dose of approximately 10 kGy or 1 Mrad to a liquid flow of 100 gallons per minute.

This machine was calibrated to determine the actual energy conversion or efficiency of treatment (where the absorbed dose was determined by a temperature measurement). Clean water was pumped through the system at approximately 460 L per minute, and the temperature-dose relationship was determined from equation (3). The total absorbed dose is related to electron beam power as follows:

$$\text{Beam Power [kW]} = \text{Dose [J/g] x Mass Flux [g/h]}/3.6 \text{ x } 10^6 \quad (4)$$

During the testing, a temperature increase of 1.56°C was measured, indicating that an actual dose of 6.5 kGy was delivered to the flowing water. From equation (4), a 75 kW beam power input should theoretically deliver a dose of 9.9 kGy to that flow of clean water.

Therefore, the efficiency of this system (beam power to energy deposited in water) is

$$6.5 / 9.9 = 66\% \text{ (efficiency)} \quad (5)$$

It should be noted that this is a direct conversion of beam power to water treatment chemistry. Also, no optimization of the system (water delivery system design, accelerator voltage, etc.) was done to make the treatment efficiency even higher. For example, at 150 gal/min, an efficiency of 72% was measured.

The utilization of any chemical for treatment of water or wastewater dramatically reduces overall treatment efficiency due to the inherent costs associated with chemical manufacturing, shipping, storing, and delivering treatment chemicals to a water stream. The calculations above demonstrate the ability of electron beam technology to be far more efficient than any other current scheme used for water treatment. The fact that electron beam technology requires only electricity, and no chemical addition, represents a major paradigm shift in the water and wastewater treatment industry.

The need to reduce energy consumption associated with water and wastewater treatment is well documented. The U.S. DOE [2-2] has determined that energy expenses represent as much as 10% of the annual budgets for local governments. A significant portion (35%) of this energy consumption is from the treatment of water and wastewater. The U.S. Environmental Protection Agency (EPA) [2-3] notes that close to 4% of the total energy used in the U.S. is for water and wastewater treatment, and this segment of energy use generates 45,000,000 tons of greenhouse gas annually. The total costs in terms of energy and/or total carbon footprint of treatment chemicals (including their synthesis, transportation, and storage) have not been accurately estimated, but it is clear that the number would be huge.

2.2 Water and Wastewater Treatment

2.2.1 Background and State of Application Development (Q1[1])

At present, there are no pilot- or full-scale electron beam systems in use in the world at either drinking water or wastewater treatment plants. This is not a fault of present electron beam technology per se, but rather the volumes needed to be treated in commercial applications, which are so large that they would require extremely high-power electron beam systems. In large municipalities, the flows to be treated are more than 100 million gallons per day (MGD).

Based on the data from the Miami experience (75 kW, 100 gpm, 10 kGy), an extrapolation of power required to deliver a dose of 10 kGy to 1 MGD of water is approximately 600 kW. Large municipalities can have treatment plants greater than 100 MGD and up to 500 MGD, implying that enormous beam powers would be needed for large municipal treatment plants. Such equipment does not currently exist. Therefore, only small-to-medium size water and wastewater treatment plants could be served with either existing commercial electron beam technologies or those envisioned in the future. However, as noted above, the unit cost of treating water with accelerated electrons, while reasonable, is not highly competitive. Significant advances in the technology to reduce costs (CAPEX) are needed to make even the existing 50–200 kW machines cost competitive in this marketplace. Further, for very high power applications, the electrical (and, therefore, operating) costs become prohibitive, even if the beam power could be provided. On the other hand, if the minimum required dose is low (in the range of 1 kGy), then the power requirements will change dramatically, and thereby, the economics will become extremely attractive for commercialization.

There are other potential environmental markets for electron beam technology as a subset of the above, e.g., the industrial waste treatment plants. Industrial wastewater quality is highly variable (compared to domestic wastewater) and often requires extensive treatment to destroy or remove toxic contaminants. Electron beam formation of free radicals may be the only treatment that would work on certain waste streams, and therefore, be worth the extra cost. In addition, industry is often able to pay higher waste treatment costs if the costs are recoverable by increased sale of product.

One of the most promising uses of electron beams would be for potable re-use of wastewater. Electrically generated radicals (HO* and e^-) would be capable of oxidizing or reducing most contaminants, as well as disinfecting the effluent. To achieve equivalent treatment, several unit processes would be required, and they still might not be able to achieve sufficient treatment (e.g., removing halogenated solvents).

Electron beam treatment of many water, wastewater, and solid waste streams present on-board ships is a viable decontamination option. The advantage of this technology is that it provides treatment with powerful oxidants (hydroxyl radical) without utilizing chemicals. This eliminates the handling and storage of dangerous chemicals on-board ships. Electron beams could be used for disinfecting raw wastewater before it is discharged at sea, or the effluent from an on-board biological treatment system that would be discharged on or near shore. This process, utilizing

[1] Refers to workshop charge specified in Section 1.3. These charge numbers are used throughout the report.

just electricity, would assure that the effluent was completely disinfected, and any other toxic compounds would also be destroyed.

Because of the penetration ability of high-energy electrons, an electron beam could also be utilized to treat any wastewater sludge that required disposal.

Electron beams also could be utilized on board ship to treat any solid waste that may contain dangerous microorganisms. Any ship that contains healthcare facilities could utilize this technology for inactivating infectious medical waste that may be generated on board. Also, if solid waste is processed utilizing a pulper, an electron beam could be used to disinfect this material before discharge overboard.

Flue gas discharges, or any gaseous emissions from ships, could also be easily irradiated by an electron beam system (see below). This radiation would generate free radicals in the water vapor and destroy organic contaminants, such as solvents or other hydrocarbons. In addition, NO_x and SO_x compounds would also be treated and removed from the stack gases emitted from a ship.

Electron beam irradiation has also been shown to be effective against invasive species transported in the ballast of ships. While the flows in ballast systems can be quite large, and current electron beam systems might not have the power to treat these flows, ships carrying modest amounts of ballast could use this technology.

2.2.2 Regulatory Framework (Q2)

Industrial regulations and effluent guidelines are summarized on the EPA website, http://water.epa.gov/scitech/wastetech/guide/industry.cfm#exist. Because of the diversity and the number of different regulations, the reader is referred to that site.

Industrial effluent treatment with electron beam systems is difficult to define, as treatment will depend on what contaminants are in the waste. At least 50 industries are considered target industries by the EPA, and they have highly variable effluent streams. However, extensive discharge and water quality standards are in place. These standards require industry to treat their effluent to a level where it can be discharged to the environment or to a municipal wastewater treatment plant, although site-specific standards depend on the ultimate disposal of the treated wastewater.

2.2.3 Economic Analysis (Q3)

The economic analysis of a commercial electron beam system, shown above, indicates that the unit treatment cost ($\$/m^3$) is reasonable for environmental applications. However, only accelerator CAPEX and power usage are considered in the estimate. A detailed analysis of costs associated with installation and operation of a full-scale electron beam system for irradiation of sludge and wastewater has been reported on the Miami wastewater treatment plant [2-4]. The system installed was a 1.5-MeV, 50-mA constant-current transformer beam with a weir for water irradiation.

Capital and operating costs are:

Capital Costs	Dollars
Installed Beam	1,850,000
Shielding, Water Syst.	500,000
Total	2,350,000
Amortization (20 yr @ 15%)	374,000/year
Operating Costs (hourly)	
Operator	20.00
Power	10.50
Water	2.50
Maintenance	8.00
Total	41.00

For this system delivering approximately a 10 kGy dose, to 100 gpm, the unit treatment cost is approximately $3.50/m^3.

The "true" total cost of a commercial electron beam system in a water treatment application, as shown above, is probably not competitive for most water and wastewater applications. However, it could be a competitive technology for *select* applications (e.g., sludge and specific industrial liquid or gaseous wastes).

Electron beam technology must compete with existing incumbent technologies. As noted above, this technology will only be able to affect treatment via oxidation or reduction, and therefore, it will compete primarily with chemical oxidants such as chlorine, ozone, or peroxide. Depending on dose, these oxidants can cost anywhere from a few cents per cubic meter treated (chlorine) to greater than $1 per cubic meter treated (ozone). A reasonable metric for cost comparison in the water treatment business is the cost to de-salt water (distillation or reverse osmosis). In other words, if the treatment cost with an electron beam is greater than $1 per cubic meter, then it would not be cost competitive, since the water could be totally deionized more cheaply than by applying an electron beam.

These economic analyses demonstrate that a ten-times reduction in electron beam cost is required in order for this technology to be truly competitive for these environmental applications. While lowering the cost of power generation ($/kW) in an electron beam system is a major challenge that needs to be addressed, total system costs (including shielding) also need to be minimized. It can be seen above that shielding costs represent a significant component in overall equipment cost, and this will be highly dependent on beam energy and beam current. It is clear that new high-power, efficient machines must be developed for large-scale environmental applications, but these machines must also have the lowest energy possible to minimize shielding requirements. Another "expensive" component of the electron beam system is "operator cost".

Therefore, new equipment designs will need to focus on reliability and sophisticated process control.

2.2.4 Performance Criteria (Q3)

Federal water quality standards govern the water quality for domestic drinking water and wastewater treatment plants. Any treatment system must at a minimum attain these standards; however, as many State requirements have primacy, it is necessary to determine if the State has promulgated more stringent ones. For large plants, this is one additional reason why they may not be a primary target for electron beam treatment until new equipment is developed.

Electron beams with higher beam power and high efficiency are needed for applications in water and wastewater treatment. The beam powers required go beyond today's capabilities. As shown earlier, a 1 MGD plant requires a beam power of approximately 750 kW in the 0.5–1.5 MeV range, which is not available today.

2.2.5 Technical Gaps (Q4)

There is a rich literature which addressees the ability of electron beam processing to achieve regulatory goals. Recent studies at Texas A&M University showed that electron beam technology can have significant value in water reuse applications, with significant reductions of microbial pathogens.

The technical gap is not whether the electron beam technology can treat the specified chemical or biological contamination, but the availability of large power electron beams that could be installed in these large plants. These applications demand high beam power in the ~MeV energy range. An appropriate development target for a single accelerator (or accelerating column) is 1 MW at 1 MeV, which represents an approximately one order of magnitude leap beyond today's commercial technology. As mentioned earlier, for smaller minimum treatment doses the economics becomes very favorable.

2.2.6 Synergistic Application-Side R&D (Q5)

The obvious area for application-side R&D is higher current, low-energy electron beam systems (1.5 MeV and less, with direct current for high efficiency) that could be used for high-strength industrial waste streams. These streams are typically characterized by high chemical contamination and lower flows. However, in most cases these would require doses beyond those needed for other applications, including biosolids treatment, which is currently regulated at 10 kGy.

2.2.7 Required R&D to Bridge Technical Gaps (Q6)

The basic R&D required to bridge the technical gaps surrounds the development of new electron beam technology that generates high power in the MeV energy range. Further research is also needed to define the treatability efficiency of irradiating water and gas steams containing mixed contaminants. R&D is also needed to develop efficient water delivery systems to optimize use of radiation. Research in free-radical chemistry is needed to discover reaction enhancement by modifying the character of the irradiated medium.

2.2.8 Barriers to Commercialization and Technology Introduction (Q6)

Several barriers exist to commercialization of electron beam technology for environmental applications. The first is the non-existence of commercial equipment that is configured for use in a high-volume drinking water, wastewater, or water reuse treatment plant. Second, the cost of an electron beam-based water or gas treatment system (capital plus operating expenses) is too high to be competitive with other technologies currently in use for most large-scale environmental applications. Third, the environmental "industry" is not familiar with electron beam technology, electron beam equipment, or radiation treatment in general. Fourth, for the technology to be used at a large scale (i.e., large market), high-power electron beam systems (>1 MW) will need to be developed.

2.2.9 Roadmap for Development (Q7)

There is a major need to develop high-power electron beams in order to be able to address a significant part of the water and wastewater treatment market. However, in parallel to this development, some basic science needs to be undertaken to understand the fundamental relationships associated with the grand challenge of environmental applications of this technology.

The discovery research that is initially required includes the advancement of technologies to overcome the limitations in the formation of high-power electron beams. Additionally, use-inspired basic research should be undertaken aimed at gaining new understanding of radiation chemistry in order to provide an understanding of dose requirements and complex chemical interactions associated with the irradiation of flowing water systems. As noted above, this use-inspired basic research is necessary to develop further interest in this technology as a viable alternative to existing environmental treatment technologies. This research effort will require approximately 3 years and cost between $2 million and $3 million.

Applied research should be undertaken with the goal of meeting technology targets such as performance enhancement, cost reduction, process efficiency, and at-scale demonstration. This research may fall within programs at the DOE applied energy offices, or other government agencies such as the EPA, National Institute of Standards and Technology (NIST), or National Science Foundation (NSF). This component of the required R&D for developing the electron beam technology would cost between $15 million and $25 million, and would require 3 to 5 years to complete.

2.3 Sludge or Biosolids Treatment

2.3.1 Background and State of Application Development (Q1)

With increasing urbanization and resulting population increases, cities around the world have to manage enormous quantities of human wastes. According to estimates, by 2017, the volume of sludge produced around the world per year will be approximately 83 million solid dry tons per year [2-5]. Currently, in the United States alone, more than 16,000 wastewater treatment plants treat around 150 billion liters of wastewater per day, generating approximately 5.6 million dry metric tons per day of treated sewage sludge. A majority (~2700) of the wastewater treatment plants in the U.S. treat less than 10 MGD. Approximately 543 facilities treat 10–100 MGD and 51 facilities treat over 100 MGD. Treatment plants in large U.S. cities such as Chicago, Dallas, Los Angeles, and Washington D.C. routinely treat 150–400 MGD. The slurry of solids and liquids generated from the treatment of wastewater is termed "sludge." Across the U.S., approximately 7 million dry tons per year of sludge are produced. The liquid waste generated from the treatment of wastewater is termed "wastewater effluent." Across the U.S., approximately 32 billion gallons per day of effluent is generated.

There is a long history of using ionizing radiation processing of sewage sludge around the world. Pilot-scale facilities using either cobalt-60 or electron beams have been demonstrated in Canada, U.S., Brazil, India, Russia, South Korea, Japan, and Austria. McKeown et al. [2-6] explored the viability of the IMPELA family of accelerators for sludge irradiation; however, due to high capital cost of the accelerator, the process was not an economical alternative. Research at Texas A&M University has shown that electron beam irradiation of sewage sludges at 10 kGy (the regulated dose for Class A biosolids) will achieve a significant reduction of pathogens [2-7, 2-8]. Table 2-3 shows the approximate log reduction of specific pathogens and indicator organisms when exposed to 10 kGy using a 10 MeV S-band linac. Overall, the study showed that pathogens and indicator organisms can be significantly reduced in sewage sludge at EPA-mandated minimum irradiation doses, confirming the 10 kGy regulated dose.

Table 2-3 Approximate (log10) reduction of different target organisms in aerobically and anaerobically digested sewage sludge when exposed to 10 kGy e-beam irradiation.

	Approximate log10 reduction at 10 kGy	
Target Organisms	**Aerobically digested**	**Anaerobically digested**
Salmonella Typhimurium	36	43
Indigenous Escherichia coli	32	40
Indigenous Aerobic spores	3	2
Indigenous Anaerobic spores	2	3
Somatic coliphage	2	2
Male specific coliphage	4	4
Poliovirus	ND	5
Rotavirus	ND	7

ND = not determined

Pillai and Reimers [2-7] also showed that when electron beam technology is coupled with oxidants such as chlorine dioxide or ferrate there was a synergistic reduction of pathogens. The combination of 100 ppm of ferrate, with 8 kGy of electron beam irradiation promoted the stabilization of aerobic and anaerobic sludge samples as indicated by test results for biological oxygen demand, volatile suspended solids, and specific oxygen uptake ratio. Overall, Pillai and Reimers [2-7] showed that when electron beam irradiation is combined with ferrate significant reductions of microbial pathogens, stabilization of estrogenic compounds and biosolids can be achieved. As ferrate has to be generated on-site, the cost associated with the ferrate addition has to be considered.

Changqing and Min [2-9] have shown that electron beam irradiation of sludges enhances the soluble chemical oxygen demand, soluble total nitrogen, and endogenous oxygen uptake rate. This finding suggests that large amounts of substrates were being solubilized, and that electron beam irradiated sludges have potential for enhanced methane production. Pre-treatment of waste activated sludge prior to anaerobic digestion could reduce the reactor solid retention time by half [2-10]. Studies in Poland [2-11] have shown that electron beam irradiation was effective at eliminating Ascaris suum eggs from cattle and swine slurries. Capizzi-Banas and Schwartzbrod [2-12] have reported that the D-10 value for ova obtained from slaughterhouse sludge was around 800 Gy while ova after laboratory manipulation had D-10 values of approximately 1.1 kGy. Using a 50 gal/min flow rate system, researchers at Kent State University using a 3 MeV electron beam system demonstrated the reduction of Ascaris ova to below detection limits at a dose of 14.5 kGy [2-13]. Today, to the best of our knowledge, there are no known electron beam facilities in operation for sludge treatment.

2.3.2 Regulatory Framework (Q2)

The EPA regulates the disposal of municipal sewage sludge to the environment in the U.S. The EPA has established specific pathogen/indicator organism limits for municipal biosolids. Biosolids are regulated based on pathogen limits, treatment processes, or testing as being either Class A or Class B biosolids. The EPA's Pathogen Equivalency Committee reviews the performance standards and treatment efficacies of new processes. Before sewage sludges can be land applied, they must meet EPA's limits (40 CFR 503) in terms of pathogens and vector attraction reduction criteria. From an ionizing radiation technology standpoint, the EPA has approved the use of 10 kGy for the treatment of sewage sludges, using either gamma irradiation (from radioactive isotopes) or electron beam irradiation to meet the definition of a process to further reduce pathogens (PFRP). As per the EPA, the use of ionizing radiation is equivalent to temperature pasteurization ($\geq 70^{o}$C for 30 minutes or longer). The treated sludge should also meet the vector attraction reduction (VAR) criteria. Thus, disinfection by electron beam technology is not the only criterion that is required for sewage sludge treatment. The stability of the treated sludge based on VAR criteria should also be taken into consideration.

In the U.S., approximately 45% of the sludge biosolids generated are land disposed, while 49% are reused for agriculture, rangeland reclamation. From an environmental perspective, the key pollutants in U.S. municipal sludge are microbial pathogens, nutrients (nitrogen and phosphorus), and minerals (potassium, calcium, magnesium, and sulfur). Heavy metals are generally not an issue in wastewater sludge streams in the U.S. since they are regulated at sources under the permitting program of the EPA's National Pollutant Discharge Elimination System. More recently, emerging contaminants such as norovirus, adenovirus, perfluorooctanoic acid, perfluorooctane sulfonate, endocrine-disrupting chemicals, and estrogenic and pharmaceutical compounds have raised some concerns in the community.

2.3.3 Economic Analysis (Q3)

In the U.S., wastewater facilities could be broadly categorized into three market segments: ≤10 MGD, 10–50 MGD, and ≥100 MGD. The standard unit for comparison across data sets for the wastewater industry is U.S. dollars per dry ton per day ($ DTPD). Economic analysis performed at Texas A&M University in collaboration with commercial linac system suppliers and sub-system suppliers has generated the treatment costs for sludge treatment given in

Table 2-4 (unpublished data). The assumptions used included delivery of 10 kGy using 10 MeV accelerators, 15-year plant life, and 8% interest rate.

Table 2-4 Electron beam technology costs for delivering 10 kGy dose for sludge treatment plants at varying capacities.

System	Capacity	DTPD	Target e-Beam Dose	Total $/dry ton
e-Beam	10 MGD/100 kW	7	10 kGy	$311
e-Beam	50 MGD/100 kW	35	10 kGy	$ 62
e-Beam	50 MGD/400 kW	35	10 kGy	$143
e-Beam	100 MGD/400 kW	70	10 kGy	$ 72

The workshop discussions related to sewage sludge centered around the current technology, the needs of the wastewater industry, and the capital and processing costs for adopting the technology. Additionally, the discussions centered around the R&D needs for accelerators to meet this market segment. Table 2-5 is an example calculation (excluding labor costs) to determine the economics (electrical costs) and capital equipment costs of electron beam processing of sewage sludge.

Table 2-5 Example calculation of costs for electron beam processing of sewage sludge.

Flow Rate in Large Cities	100 MGD, which translates to 24000 dry tons per year based on 2% sludge
Assumptions	70% electron-beam utilization; 50% wall-plug to beam power efficiency
Flow Rate (dry tons/day)	65.75
Dose (kGy)	10
Beam Power (kW) (based on 70% beam efficiency)	487
Electrical Power (kW) (based on 50% electrical efficiency)	975
Electricity Cost ($kW-hr)	0.09
Operating Cost ($/day)	2106
Specific Unit Cost	$32 /dry ton
Capital Costs	
Beam Cost ($M/MW)	10
System Cost ($M)	4.9
Annualized Cost ($M/year)	0.49
Annualized Cost ($/day)	$ 1335.42
Specific Capital Cost ($/dry ton)	$20.31
Total Cost (electrical + capital cost, excluding labor, product handling , etc.)	$52.31/dry ton

Further details on calculating operating and capital costs can be found in Miller [2-14].

2.3.4 Performance Criteria (Q3)

Large municipalities would need to treat large volumes of sludge. Full-scale industrial treatment requires MW–beam-power class electron beams. Unlike wastewater effluent treatment, sludge treatment is a batch process that does not generally require a 24/7 operation. Therefore, the 100% redundancy may not be a pre-requisite in some facilities. However, wastewater industry workshop participants did mention that, in some large facilities, sludge treatment is a 24/7 operation, and in such instances system redundancy is a prerequisite.

2.3.5 Technical Gaps (Q4)

The technical gaps in demonstrating the applicability of accelerator technology for use in biosolids and wastewater treatment applications are listed below. Accelerators should be so designed so that they are able to address the following needs:

Biosolids:

- *Viscosity Reduction*: Decreasing sludge viscosity will potentially save electricity cost of pumping sludge.
- *Methane Production*: Demonstrating increase in methane production with electron beam irradiation will be of significant value to the wastewater/sludge industry.
- *Dewatering*: Increasing dewatering efficiency and reduction in polymer usage after electron beam treatment will optimize the dewatering facility and reduce chemical cost and, potentially, sludge hauling cost.
- *Pathogen Reduction*: Demonstrating required reduction of pathogens after electron beam irradiation will assist in achieving Class A certification and sale as fertilizer for potential non-food agriculture market.
- *Emerging Contaminants*: Demonstrating the reduction of emerging contaminants after electron beam irradiation will potentially assist in reaching the food agriculture market.

Wastewater Effluent:

- *Disinfection Dosage*: Validating the electron beam dosage for wastewater effluent for required pathogen reduction will potentially provide an alternative technology to currently used technologies such as chlorination and ultraviolet treatment.
- *Reduction of Emerging Contaminants*: Identifying the emerging contaminants and demonstrating the reduction of those particular emerging contaminants after electron beam irradiation will also potentially provide an alternative technology to compare with currently used technologies such as reverse osmosis.
- *Reduction of Dissolved Salts*: Demonstrating the reduction of dissolved salts will provide a significant market in desalination applications.

For industrial-scale sludge treatment for large municipalities (>100 MGD), the minimum requirement is 10 MeV, 1 MW-class accelerator technology. This technology is not commercially available today. Having a demonstration facility in the U.S., even one based on existing accelerator technology, would be of significant value to the wastewater industry. At such a facility, the technology can be optimized in terms of designing the material handling needs, gaining a deeper understanding of the specialized labor requirements, refining the operating costs and treatment efficiencies, and developing a blueprint for integrating this technology into contemporary wastewater treatment plants. Thus, a key technical gap for commercial use of the electron beam technology for sludge treatment is the lack of availability of the 10-MeV, 1-MW class electron beam systems.

2.3.6 Synergistic Application-Side R&D (Q5)

The introduction of electron beam technology into the wastewater treatment industry can have a variety of collateral benefits. The technology could foster the rapid development of value-added products from the treated sludge, such as high value fertilizers, bioplastics, and soil amendments, and could lead to enhanced methane production. Electron beam technology could be creatively combined with other pre-existing processes and technologies, such as dewatering and anaerobic digestion, to enhance methane production. Enhancing the generation of methane with electron beam pre-treatment of sludge could be of significant value to utilities that are targeting net neutral energy consumption and nutrient and energy recovery needs.

2.3.7 Required R&D to Bridge Technical Gaps (Q6)

There is a technical gap between today's COTS electron beam technology and the needs for today's full-scale municipal sludge treatment. Table 2-6 highlights the R&D needs for accelerator technologies to meet the sewage sludge treatment applications.

Table 2-6 Listing of potential R&D topics to facilitate linac technology for sludge treatment.

Application	Near –Term (1-5 years)	Mid-term (5-10 years)
Sludge treatment (disinfection + other potential applications)	• Improvements in electron-beam utilization efficiency • Improvements in wall-plug to beam-power efficiency • Improvements in technology operation • R&D into specific applications of technology • Improvements in beam-line and target /applicator • R&D into sludge material handling for electron beam systems • R&D on methane generation, sludge odor abatement, sludge viscosity reduction, aerobic and anaerobic digester loading capability, and sludge dewatering efficiency	• R&D into efficient RF power sources • R&D into driving manufacturing costs down • Technology scaleup • Development of turn-key designs customized for the wastewater industry

2.3.8 Barriers to Commercialization and Technology Introduction (Q6)

Roadblocks in technology adoption and commercialization are as follows:

Biosolids:

- *Financial and infrastructure participation from a utility for demonstration project*: Since the technology is ready for commercial use at least at small-scale, if a utility were to assume a portion of the financial responsibility and provide the land for the equipment installation and associated piping, then studies to evaluate the "value proposition" could be made. The value proposition would be that an increase in methane production, ease of dewatering, and production of Class A sludge will offset the cost of the electron beam accelerator and associated O&M cost.
- *Education and awareness of safety of utilizing electron beam technology*: An effort is needed to educate and increase awareness in utilities on the safety of electron beam accelerators in terms of radiation.

Wastewater Effluent:

- *Due to 100% redundancy, the capital cost is relatively high*: Per EPA regulations, there has to be 100% redundancy. That will increase the capital cost significantly.
- *Regulatory approval*: The minimum dosage for disinfection has not been established by the EPA. The minimum dose limit is critical because it will directly influence electrical costs.
- *High electrical cost*: Electrical cost is significantly higher than that for other currently utilized disinfection technologies by an order of ten if the minimum dose is 10 kGy (see above). Therefore, the amortized cost of the accelerator may not be the dominant component of life-cycle costs.
- *Facility modifications*: Heavy facility modifications will be needed to accommodate an electron beam accelerator in an existing treatment train. The potential modifications would be influent piping changes, possible additional pumping, and discharge piping.

The sludge industry is inherently conservative in its approach to new technologies. Technology adoption is a slow process that requires lengthy laboratory testing and piloting procedures. Nevertheless, a growing openness to new approaches is evident, especially to keep up with tightening regulations and the need to solve specific issues. Cost efficiency is still a key factor determining the adoption of new technologies. The COTS electron beam technologies do not have an adequate combination of power and energy to meet current wastewater industry needs. In the U.S., cities that have the capital resources to invest in electron beam technologies need technology solutions to treat solids and effluents in the 100–200 million gallons per day scale. Currently, there are no commercial solutions for this need. Another technical issue that is an obstacle (perceived or real) is the lack of reliability of accelerators. Wastewater treatment plants require significant reliability and system redundancy. There are no data whatsoever on the reliability of high-energy accelerator systems that operate in a real wastewater environment. Further, there is a lack of awareness of this technology among practicing environmental engineers. The reasons for this could be linked to the leading environmental engineering textbooks lacking any meaningful and substantive discussion of this technology. Thus, it is not surprising that graduating environmental engineers have limited exposure to the core technologies. This is exacerbated by widespread misunderstanding and confusion about the technology in terms of energy, power, penetration, dose, etc. Other market barriers include the erroneous perception that (i) electron beam systems lack sufficient penetration capability, (ii) the economics are cost prohibitive, (iii) the technology is not commercially feasible, and (iv) the technology makes the water radioactive. The actual market barriers are (i) lack of technology for real-life high-volume applications, (ii) high up-front costs, (iii) lack of U.S. technology vendors, (iv) lack of skilled personnel to repair and service the installations, and (v) lack of effective industry outreach programs

2.3.9 Roadmap for Development (Q7)

Presently, electron beam technology exists for installation at a treatment demonstration plant. The costs for treating sludge at 10 kGy will be in the range of $50–80 per dry ton for >100 MGD treatment plants (Tables 2-4 and 2-5). As Table 2-4 indicates, the treatment costs will be higher for smaller scale plants. A path forward for this technology will be for a consortium of large municipalities to invest in the design and construction of a demonstration plant with a 10 MeV, >100 kW configuration. This will allow industry stakeholders to obtain empirical data on performance, cost, infrastructure needs, and synergistic applications. These types of installation can help stimulate federally supported and industry supported R&D into higher power accelerators to meet large throughput volumes and high value applications. The availability of large-volume demonstration plants will help small- to mid-range treatment facilities to understand the potential of this technology. Importantly, the environmental engineering consultant and practitioner community will obtain a greater knowledge of the technology. As stated above, some of the barriers to the adoption of this technology can be quickly overcome if the U.S. has one or more large-scale demonstration facilities. The actual market barriers outlined above will also be mitigated with a functioning large-scale demonstration facility.

2.4 Flue Gas Treatment

2.4.1 Background and State of Application Development (Q1)

The treatment of flue gas, SO_x and NO_x, by electron beams was first reported in 1972 [2-15]. Since the initial report, many additional studies have reported on various aspects of the process. The overall conclusion was that electron beam irradiation is effective in controlling both SO_x and NO_x; however, NO_x control requires considerably more dose, and hence more power than that for SO_x control. Tests were performed for boilers fired with hard coal, high sulfur lignite, and high sulfur heavy oil. More recently, there are reports that the process is also applicable to volatile hydrocarbon (VOCs) removal in flue gas [2-16]. The possibility of the process applications for mercury control was demonstrated at the batch laboratory scale. The applicability of the process for high power diesel engines at cargo ships was studied as well [2-17].

A number of facilities worldwide have installed electron beam systems to treat flue gas [2-18, 2-19, 2-20]. All of these plants use DC low-energy systems (<1 MeV). It is noteworthy that a recent summary of the field by Han [2-21] does not include reference to any accelerator technology not already in use in the 1990s.

Furthermore, none of the facilities put in place since the 1990s is in operation, apparently due to failures and less-than-adequate reliability of the low-energy, high-power accelerator systems, but also due to lack of user support. This testimony to the apparent unreliability and possible unattractiveness of those early accelerator systems provides strong motivation for the goals enunciated in the Introduction: namely, to foster new research and development on high-power electron accelerators relevant for pollution remediation that are technologically simple, relatively low cost, and rugged; have long operating lifetime on a 24/7 basis; and occupy a modest real estate footprint.

The system with the longest operational history was in Poland and consisted of four 260-kW, 700-keV accelerators supplied with electricity from two power supplies. Two heads are installed in series on two parallel process vessels. Double irradiation reduces energy consumption by 10%. The system produces a high quality fertilizer, which is sold to help defray the cost of treatment.

A quantitative perspective on the requirements for an electron beam system that would be suitable for remediation of a flue gas waste stream can be gleaned from an example (see Hirshfield et al. [2-22]). Parameters for this system were selected to apply to emissions from a 100 MWe power plant burning high-sulfur coal, with the aim of achieving significant reduction in SO_x emissions, but only moderate reductions in NO_x emissions. The system design incorporated two pulsed linear accelerators providing two-sided irradiation and uniform dose across the duct. Each linac was designed to provide a 2-MeV beam with a peak power of 2.5 MW and an average power of 125 kW (250 kW total average power) suitable for irradiation along an 8–10 m chord crossing the duct. With the 3 kGy dose that this system provided, removal of more than 70% SO_x and 30% NO_x would be possible, depending on the temperature and humidity of the flue gas and on the addition of ammonia. For greater degrees of removal, especially for NO_x, a 9 kGy dose would be desirable.

If one scales the 250 kW e-beam power for a 3 kGy dose in the above example to 9 kGy, then 750 kW of average e-beam power would be required for a 100 MWe plant burning coal with the same degree of pollutants. But many coal-burning plants have greater capacity, with 500 MWe being not uncommon. In such units, multiple parallel systems should be used since this concept is used for electrostatic precipitators (ESPs) that are installed upstream of electron beam systems to assure purity of the byproduct. In any case, reliability in the use of e-beam remediation would be stronger if a number of moderate-level machines operating in parallel were to be used. For example, if each machine provided 0.5–1.0 MW average e-beam power, then 5-10 units would be used, so a temporary outage of one machine should not represent an undue loss of performance. Accordingly, a prudent approach for renewed R&D is to work toward demonstration of electron beam accelerators with 0.5–1.0 MW average power that, as stated above, are technologically simple, relatively low cost, and rugged and have long operating lifetime on a 24/7 basis and a modest real estate footprint.

2.4.2 Regulatory Framework (Q2)

At present only SO_x is regulated for coal-burning power plants in the U.S. There have been attempts to regulate NO_x and mercury. In 2005, EPA developed the Clean Air Interstate Rule, a cap-and-trade program intended to reduce SO_2 and NO_x emissions beyond the levels defined by the acid rain program in the eastern half of the United States. That rule was challenged in the courts. Nevertheless, 91 GW of coal-fired power capacity was retrofitted with flue gas desulfurization (FGD) scrubbers between 2005 and 2011. By the end of 2011, 60% of the U.S. coal fleet had FGD scrubbers installed. By the end of 2011 67% of the fleet had either a selective catalytic reduction (SCR) system or a selective non-catalytic reduction (SNCR) system installed for NO_x control.

While the U.S. does not regulate NO_x emissions from coal burning power plants, they are regulated in most developed countries.

Recently, electron beam irradiation has been shown to be effective in mercury control in bench-scale tests [2-17]. This study demonstrated the oxidation of 98% of gaseous mercury at medium dose levels, a result which may become significant as mercury standards evolve.

2.4.3 Economic Analysis (Q3)

Present flue gas treatment technology is adequate to meet existing regulations. The removal of SO_2 and NO_x from flue gas is normally realized by a combination of de-SO_2 and de-NO_x methods. The removal efficiency of both systems, that is, electron beam flue gas treatment (EBFGT) and combined wet flue gas desulfurization and selective catalytic reduction, is comparable. The desulfurization efficiency is at least 95% (as high as 98%) in the case of EBFGT technology, while it is reported at the level of 95–99% in the case of the wet FGD technique. Similarly, NO_x removal efficiency based on EBFGT technology is at the level of 70% while SCR efficiency is usually 70–80%. The efficiency of the SNCR is much lower.

An economic comparison of EBFGT with conventional technologies is presented in Table 2-7. At present, there is no compelling argument for installing electron beams for flue gas treatment in the absence of additional regulatory pressure. If standards evolve to include NO_x and/or mercury control, then the economic considerations could make electron beam technology a more attractive approach.

Table 2-7 Economic analysis of flue gas treatment methods.

Flue gas treatment method	**Investment cost (U.S.$/kW)**	**Annual operational cost (variable) (U.S.$/MW)**
Wet SO2 scrubbing:	190 – 240	12,750 to 28,050
SCR	60 – 110	3,800 – 4,600
SNCR	15 – 30	2,500 – 3,000
Combination of methods:		
Wet de-SO2 + SCR	250 – 350	16,550 – 32,650
Wet de-SO2 + SNCR	205 – 270	15,250 – 31,050
EBFGT	160	7,350

Data from 2003.

2.4.4 Performance Criteria (Q3)

The goals for the removal of SO_x and NO_x in typical coal-burning power plants are targeted to be 90% and 70%, respectively. However, in the U.S. there are no regulations on NO_x as of yet.

The required availability of the system, including accelerators, should be at least 92% of boiler operation time (7000–8000 hours per year). As described above, multiple accelerators in the 0.5–1 MW range are required for a full-scale implementation in a large coal-burning plant.

2.4.5 Technical Gaps (Q4)

Problems reported at industrial plants in Japan and China were connected with the failure of accelerators, and similar problems occurred at an installation in Poland. These installations required high power and, therefore, utilized designs capable of providing more than 250 kW of electron beam power. Reported difficulties were associated with inadequate electron-beam system availability, falling short of that required to meet boiler operation times of 7000–8000 hr/yr. These difficulties highlighted the importance of overall system design for availability, manufacturing, and quality control. One potential reason for some of the quality issues may be that the equipment manufacturers themselves have not performed sufficient research in the development of very high power accelerators capable of meeting high availability goals. In these systems, the accelerator is not the only challenging system; special attention should also be paid to electrostatic precipitator engineering.

Demonstration is needed to show viability and to help estimate costs of a 0.5–1.0 MW electron beam facility in the beam energy range 1–2 MeV. The facility should include not only an accelerator with efficiency greater than 95%, but also a state-of-the-art DC power supply with an efficiency greater than 90% for the radio-frequency (RF) source, whose efficiency must be >90%, and a rugged beam transmission window whose beam power loss must be less than 5%. Thus the goal for the e-beam system should be a wall-plug efficiency greater than 70%. Since that still means that creating a 1-MW beam requires another 0.4 MW of wasted power, this very challenging goal will require R&D at full power levels before all known and unknown issues can be overcome.

2.4.6 Synergistic Application-Side R&D (Q5)

Increased reliability would also assist in other applications of electron beams for environmental applications.

2.4.7 Required R&D to Bridge Technical Gaps (Q6)

There has been little progress in low-energy electron accelerator engineering since the 1990s. There have been no reports regarding industrial/environmental applications of breakthrough solutions. There has been little technology transfer from the development of modern accelerators (like superconductivity and energy recovery) into the commercial marketplace. National laboratories do not typically perform research in this field, and the private sector cannot invest in R&D, since it would sell only a few machines a year and does not have funds to cover such activities. There are significant technical gaps in four categories: the accelerator itself, the RF source efficiency, the power supply efficiency, and the beam window.

2.4.8 Barriers to Commercialization and Technology Introduction (Q6)

The lack of NO_x standards is a barrier to commercialization. Until the implementation of regulations for NO_x control and possibly mercury control, it is unlikely that electron beam treatment would be used in the U.S. Worldwide, the situation is somewhat different as NO_x is regulated elsewhere.

2.4.9 Roadmap for Development (Q7)

The near-term reliability of the low-energy, high-power accelerator systems has to be improved to facilitate widespread adoption of the technology. It is possible that the commercially available systems, if used, would satisfy this need.

New accelerators using updated engineering solutions are needed in the fields of transformers, new electronics, materials for windows, types of cathodes, and so on.

In the long term, a full-scale industrial unit using new high power accelerators should be developed, targeting a boiler size of 100 MW. R&D is needed to develop compact, low-cost, highly-efficient accelerators in the 1–2 MeV, 1-MW range; to develop highly efficient MW-class DC power supplies and RF sources; and to improve upon existing window designs for high average power beams.

2.5 Medical Waste

2.5.1 Background and State of Application Development (Q1)

There is an application for electron beam-based technology for the disinfection of hospital wastes. Currently, hospital wastes, for the most part, are transported off-site for incineration or other treatment processes. Incinerator technologies have certain salient advantages: 1) the ability to dispose most waste items and forms, 2) suitable for large volume reductions of medical waste, 3) complete sterilization and potential detoxifications, 4) generation of heat that could be recovered and reused, 5) incinerator residues that are unrecognizable and therefore suitable for environmental (landfill) disposal, and 6) possibility of favorable life-cycle cost. However, incinerator technologies also have major disadvantages. These include potentially high costs, difficulties in siting, need for stack emission permits which pose related permitting difficulties, and growing public and environmental group opposition. The emissions from incinerator facilities include carbon monoxide, NO_x, particulates, hydrocarbons, dioxins and furans, metals (e.g., Cd, Cr, and Pb), gaseous acids (e.g., HCl), and BTEX organics (e.g., benzene, and toluene).

The availability of a non-incinerator based technology can be advantageous from a variety of perspectives, including environmental benefits, reduced carbon footprint, and reduced energy costs. Electron beam technology will not replace incineration technologies, given the types of wastes that fall under the umbrella of medical wastes. Medical waste treatment requires doses of approximately 50 kGy. This in turn requires beam powers of approximately 250 kW (see example below), and high beam energy for adequate penetration. Linac technologies can be effective for on-site treatment of liquid and solid wastes, provided that small-footprint. low-capital intensive technology becomes available. Electron beam systems with small footprint, high throughput, and low energy, such as those developed commercially may be applicable for low-volume, batch-scale liquid medical wastes, where pathogen disinfection is the key application. Electron beam technology could also have value in treating the exhaust from such incinerator facilities, where the cost of filters currently is around $20,000 per month. The amount of medical waste generated per month was estimated to be approximately 4 million pounds in the U.S.

2.5.2 Regulatory Framework (Q2)

There are significant differences in the management of hospital wastes globally. These differences depend on the socio-economic conditions, available resources, treatment technologies, and capabilities to monitor and manage such wastes. The World Health Organization defines wastes from research laboratories, research centers, health-care facilities, etc., as "health-care wastes." The EPA uses the term "medical wastes" to include all waste materials generated at health care facilities, such as hospitals, clinics, physician offices, dental practices, blood banks, veterinary hospitals/clinics, and medical research laboratories. The different states in the U.S. have specific regulations governing such medical wastes. Additionally, the term "regulated wastes" is used to highlight the potential for infection transmission and the applicability of specific regulations. Only approximately 6–8% of the waste generated from hospitals in the U.S. is considered "regulated medical wastes" that require specialized treatment. Landfilling of treated medical wastes is permitted in many states in the U.S. In Texas, for example, medical waste may be treated on-site or off-site at an authorized treatment facility that has to be operated under specific approvals. At a minimum, operators of medical waste treatment facilities should demonstrate a 4-log reduction of *Bacillus* spores. Treated medical waste can be disposed in a permitted municipal solid waste landfill.

Less than 10% of the "regulated wastes" in the U.S. is incinerated (Holboy, 2015 –unpublished data). There are alternatives to incineration, including microwave, autoclaving, and chemical treatments such as ozone disinfection. However, there are technical challenges with these technologies to meet the process specifications of medical wastes. Additionally, 31 states in the U.S. require incineration of certain medical wastes. For example, incineration is required for the disposal of body parts.

2.5.3 Economic Analysis (Q3)

The medical waste industry currently expends approximately $0.18 per pound of hospital waste by autoclaving, which is a less expensive treatment technology compared to incineration. Table 2-8 details the electrical and capital equipment costs (excluding shielding, material handling systems, etc.) for an accelerator-based technology for treating hospital wastes.

As can be seen in Table 2-8, the costs for treating medical waste will be an order of magnitude cheaper than currently employed technologies. Additionally, since accelerator-based technologies have reduced carbon footprint and do not involve large inputs of energy, the medical waste industry may find that this technology is able to exceed its requirements.

Table 2-8 Simplified electrical operating and capital (linac) equipment economic analysis.

Regulated Medical waste volume (U.S. total)	100 million pounds per month
Assumptions	70% beam utilization; 50% wall-to-beam electrical efficiency
Flow rate (million lb/day)	3.3
Processing rate requirement (kg/sec)	17.5
Sterilization dose (minimum) (kGy)	50
Required beam power (kW)	1250
Electrical wall power (kW) (assumption 50% efficiency)	2500
Electricity cost ($kW/hr) (assumption $0.09 kW/hr)	0.09
Operating cost ($/day)	5400
Specific unit cost ($/lb)	0.0016
Capital equipment costs (linac only)	
Beam cost ($ M/MW)	10
System cost ($M)	12.5
Annualized cost (10 year)	
$M/year	1.25
$/day	3430
Specific unit cost ($/lb)	0.001
Total cost (electricity + capital) ($ per pound)	0.0026

2.5.4 Performance Criteria (Q3)

For the medical industry to adopt electron beam technology today, there is a need for 10-MeV, 100-kW machines. Dual modality equipment combining X-ray and electron beams would be ideal. Advanced imaging and process control tools are needed to identify and plan electron beam or X-ray treatments based on different incoming product densities, bulk volumes, etc. Process tools are also needed to measure delivered and absorbed doses parametrically. Medical waste industry personnel are concerned about the possible radiation exposure from this technology. Significant opportunity thus exists for the accelerator community to develop effective outreach and education programming to address this misconception.

2.5.5 Technical Gaps (Q4)

Currently, large-scale demonstration of electron-beam-based facilities to treat hospital wastes can be built and operated with COTS technologies. A large-scale demonstration facility can be operated using the COTS 10-MeV, 10-kW accelerator configuration. A 10 MeV, 100 kW (electron beam + X-ray) accelerator configuration would be needed to fully commercialize this technology.

2.5.6 Synergistic Application-Side R&D (Q5)

The introduction of electron beam technology to service the hospital and medical waste industries will spur the development of synergistic applications, such as treatment of autoclave effluents and potential recycling of high value metals from medical waste streams. Also possible is the use of electron beam technology for treating incinerator exhaust gases. Given the recent awareness regarding highly infectious wastes such as from Ebola patients in the U.S., small footprint accelerator systems that can treat medical wastes from high containment facilities can also be considered a synergistic application.

2.5.7 Required R&D to Bridge Technical Gaps (Q6)

Table 2-9 highlights the near- and long-term R&D needs of the medical waste industry.

Table 2-9 R&D needs to bridge technical gaps in medical waste treatment.

Application	Near –Term (1-5 years)	Mid-term (5-10 years)
Hospital/medical waste disinfection	• Development of imaging tools and process controls tools to identify and plan treatment for different products and materials • Development of process control tools that will assist the parametric determination of delivered and absorbed doses	• Design of advanced imaging tools to optimize dose distribution by modulating energy and dose rate parameters • Development of 10 MeV, > 100 kW compact electron beam systems

2.5.8 Barriers to Commercialization and Technology Introduction (Q6)

A primary barrier to commercial adoption appears to be the lack of awareness of this technology among the waste industry. There is no technology roadblock at this time. While COTS technology is available to meet this industry's current needs, a comprehensive factual education and outreach program is needed to disseminate the value of this technology to the waste industry stakeholders. The availability of such educational resources can be of high value in terms of commercialization.

2.5.9 Roadmap for Development (Q7)

A 10 MeV, 100 kW facility should be built as a full-scale demonstration facility in the U.S. This technology will be well suited for a large medical waste hauling company. To accelerate this adoption, an effective education and outreach program targeting the medical waste and hospital industries would be valuable. The full-scale demonstration facility will enable the waste industry to derive precise economic analyses, understand the staffing requirements, and stimulate synergistic applications of this technology in this market segment.

2.6 Environmental Remediation of Hydrocarbon Contaminated Soils

2.6.1 Background and State of Application Development (Q1)

Pollution of soils by organic hydrocarbons is a major global environmental issue. Pollution may occur quickly from large oil spills or slowly through seepage of lighter liquid fractions at drill sites over decades, resulting in contamination of soil and groundwater [2-23]. The importance of this issue is self-evident, given the importance of soil as a natural resource and its role in maintaining life, and the fact that soil is a non-renewable resource due to its low rate of renewal [2-24]. The implications of soil pollution are destruction of local ecosystems, contamination of drinking water and farmland, and millions of dollars in economic damage. To minimize the consequences of soil pollution, soil remediation technologies must be fast, efficient, and economically viable at large scales.

Of most immediate importance is remediation of soils contaminated with crude oils. Crude oils contain a wide range of hydrocarbon fractions, including light, medium, heavy, and very heavy compounds. Lighter fractions are clear, highly viscous liquids that are naturally removed through environmental exposure and biodegradation. Very heavy components, such as tar and asphalt, are generally immobile and thus pose no threat to the environment. Medium to heavy fractions, however, do not degrade as quickly as light fractions, but are still mobile in the soil. These pose the greatest threat for environmental damage.

Medium fraction concentrations, referred to as diesel range organics, are typically the standard for evaluating contamination levels. Remediation techniques seek to change the soil contaminants chemically, thermally, and/or biologically [2-24]. Confinement techniques that restrict contaminant mobility and/or decontamination techniques can be used to permanently remediate soils [2-24]. On-site and in-situ methods provide the best alternative; however, all methods but thermal desorption are expensive and high energy, and have a long time frame [2-25].

Electron-beam irradiation processes are highly controllable and leave no residual radiation, lending them to many industrial applications such as but not limited to bond cracking, cross-linking, polymer degradation, sterilization, pasteurization, and vulcanization [2-26, 2-27]. Irradiation has been investigated as a method to break up trace contaminant in soils and water for several decades. A challenge in such applications is that the approach is not targeted and significant inefficiencies occur in the processing of the uncontaminated bulk. Recently, the irradiation of high contaminant (1% to 30%) soils and sludges has been investigated with greater efficiency. One application is the removal of petroleum hydrocarbons from soils. The EPA (and similar regulatory bodies) mandates "total petroleum hydrocarbon" (TPH) concentrations of less than 1% (typical for industrial sites). High dose treatments (100 kGy to 1 MGy) have also been shown to be relatively efficient and effective methods of reducing TPH by as much as 99%.

Electron beam irradiation has been shown to be able to remove hydrocarbon contaminants from soil. For soils ranging in contamination from 2% to 10% by weight hydrocarbon, reductions of 10% to as high as 99% of contamination have been demonstrated. This requires dosages ranging from 100 kGy to 1 MGy, depending on soil water content, soil type, and initiation contamination. High energy beams offer higher penetration depths, less pre-processing, and potentially higher throughput in application. Figure 2-1 shows a decontamination cross section for a 10 MeV beam into a high-clay-content 5% contaminated soil [2-28]. The blackened soil is in the higher dose region, and a carbonaceous char remains while the oil contamination (quantified by TPH) has been reduced to less than 0.5%.

Figure 2-1 Decontamination cross section for a 10 MeV beam into a high-clay-content 5% contaminated soil [2-28].

As a quantitative example, treating 1000 cubic yards of soil per day at 500 kGy dose requires a beam power of approximately 11 MW, as shown in the example below.

One aspect of the efficacy in electron beam irradiation is the direct volumetric energy addition afforded by the penetrating beam. Unlike many other methods, irradiation allows for volumetric heating. A second synergistic process is the radiation-induced chemistry, specifically the cracking of heavy hydrocarbons into lighter, more easily evaporated and biodegraded hydrocarbons. The cracking of heavy hydrocarbons in contaminated soils arose out of ongoing research into the cracking of heavy hydrocarbons in crude oil processing. Specifically, electron beam accelerators with high power and energy have been investigated for the processing of heavy and viscous crude oils at the well head to increase their value and transportability. In such applications, electrons induce the formation of radicals, which under the right conditions lead to cracking of large asphalt-like molecules [2-29].

For example, electron beam radiation has been investigated as a way to upgrade heavy hydrocarbons [2-30]. In one experiment, 12 API heavy crude oil was irradiated with a 2 MeV beam at a 360 kGy dose. The result was conversion of roughly 17% and 20% of >450^{o}C hydrocarbon residue (i.e., hydrocarbons that boil at 450^{o}C) for dose rates of 20 kGy/s and 37 kGy/s, respectively [2-31]. This finding indicates that the conversion is not strongly dependent on dose rate, and that electron beams can successfully degrade very heavy hydrocarbon compounds. Additionally, treatment of atmospheric residues using radiation thermal cracking has been demonstrated to produce greater reductions in viscosity and increases in distillable compounds than typical thermal cracking techniques [2-32, 2-33].

2.6.2 Regulatory Framework (Q2)

The remediation benchmark established by the EPA is < 1% total petroleum hydrocarbons. Thus, soil remediation by electron beam technology should be directed at achieving this benchmark. Since there is a regulatory framework, this technology, if shown to be commercially feasible could be quickly commercialized.

2.6.3 Economic Analysis (Q3)

Table 2-10 provides a simplified economic analysis detailing the electrical costs and capital costs for accelerator-based technology to meet the commercial industry needs.

Table 2-10 Simplified electrical operating and capital equipment economic analysis.

Remediation of hydrocarbon contaminated soils	Target need: 1000 cubic yards per day
Assumptions	70% beam utilization; 50% wall to beam electrical efficiency
Flow rate (cubic yards/day)	1000
Processing rate requirement (kg/sec)	15.93
Sterilization dose (minimum) (kGy)	500
Required beam power (kW)	11,379
Electrical wall power (kW) (assumption 50% eff)	22,757
Electricity cost ($kW/hr) (assumption $0.09 kW/hr)	0.09
Operating cost ($/day)	27,309
Specific unit cost ($/cubic yard)	27
Capital Equipment Costs (linac only)	
Beam cost ($ M/MW)	10
System cost ($M)	113.8
Annualized cost (10 year)	
$M/year	11.38
$/day	31174.17
Specific unit cost ($/cubic yard)	31.17
Total cost (electricity + capital) ($ per cubic yard)	**58.17**

2.6.4 Performance Criteria (Q3)

The minimum dose required will be 500 kGy. Based on a minimum throughput rate of 1000 cubic yards per day, it is evident that a 10 MeV, 10 MW accelerator is required. The system should be movable from one contaminated site to another site with minimal downtime for setup and takedown. The movable system can be envisioned to be shielded with soil from the site. Movability is the key, with preferably a 1-week setup time.

2.6.5 Technical Gaps (Q4)

High-energy (10 MeV), high-power (1–10 MW) accelerators are needed for actual commercial use. A subscale demonstration could be set up using commercially available technology. Technology for movability/portability is non-existent at the present time, however.

2.6.6 Synergistic Application-Side R&D (Q5)

The availability of movable high-energy, high-power (>1 MW) accelerators will also stimulate applications in conversion of crude oils at well heads. These applications require doses in the range of 500 kGy to 2000 kGy at 1 MW and higher at single wellheads.

2.6.7 Required R&D to Bridge Technical Gaps (Q6)

High energy, high power (≥1MW), movable/portable accelerators are needed. R&D on smart shielding, especially the ability to detect aberrant performance, is needed. Additionally, a significant amount of science is still needed in terms of the dose rate chemistry as it relates to hydrocarbons.

2.6.8 Barriers to Commercialization and Technology Introduction (Q6)

The lack of availability of 10-MeV, ≥1 MW movable accelerator technology is a key impediment in terms of commercialization.

2.6.9 Roadmap for Development (Q7)

A large-scale accelerator demonstration facility (10 MeV, ≥700 kW) in the field will be a major boost for the commercialization of this technology. This demonstration facility can be used to optimize the process, better understand the critical operational parameters, and delineate the vulnerabilities in terms of operations, radiation hazard shielding, environmental impact assessments, operator training, and community and industry stakeholder education and outreach. The availability of a ≥1 MW movable accelerator technology will have a significant positive impact on commercialization in the environmental remediation market. To address the conversion of crude oil market, high energy, high power (MW-class and greater) accelerators are needed.

2.7 Asphalt Treatment

2.7.1 Background and State of Application Development (Q1)

According to the Federal Highway Association (FHWA), Federal, State, and local governments maintain nearly 3.7 million miles of paved public roads fabricated from asphalt concrete. Despite recent attempts to improve the asphalt concrete binder via chemical modification prior to road construction, the resulting asphalt highways still suffer from rapid aging, particularly in climates that experience frequent freeze-thaw cycles. Current asphalt road surfaces require a continuing cycle of repair that consumes enormous amounts of energy and costs taxpayers more than $50 billion per year.

Fermilab has patented and is in the process of demonstrating a new technique in the way asphalt roads are built, with the goal of substantial extension of the lifetime via a drop in technology with modest added cost during construction. The technique makes a fundamental change in the bitumen binder that is currently used with gravel to form asphalt roads by replacing it with a “radiation modified binder” (RMB), a material whose properties can be modified via irradiation. The concept calls for the use of mobile electron beam accelerators mounted in trailer trucks for in-situ modification of the RMB to yield a material that is both strong and tough as well as highly resistant to cracking during thermal cycles. With this process the goal is to double highway lifetimes. The advantages of extended life asphalt include a substantial decrease in use of heavy machinery for road repair; decreased fuel usage and carbon footprint; decreased energy use to heat hot mix asphalt; reductions in fuel use and commuter wait times in traffic due to asphalt highway repairs; increased workable lifetime of the hot mix asphalt; ability to modify the mechanical properties of the binder after the road has been constructed; ability to customize binder properties to best meet the climate and usage; and a substantial saving of taxpayer dollars.

“Radiation modified binder” (RMB) is used herein to mean any binder material employed to construct an asphalt concrete-like road surface in which the binder has been chosen such that its properties can be modified with electron beams in situ. Electron beams can drive chemical reactions and promote cross-linking of materials, leading to increased strength and toughness. Currently, applications of electron beam cross-linking material employ an accelerator in a fixed location. Improvements in accelerator design now allow for the design and construction of efficient, compact, high-power, high-energy electron linear accelerators. As a consequence, it is now possible to design and build accelerators with beams exceeding 1 MW that can fit on a semi-truck to drive chemical reactions, such as crosslinking in situ, including on road surfaces.

The electron beam energy determines the penetration depth. Maximum beam energies for industrial processes are typically limited to 10 MeV to avoid activation of target materials. The electron penetration depth in asphalt concrete is approximately 2 cm. However, the X-rays produced penetrate further. Simulations indicate that radiation-induced chemical modification of the binder is feasible in at least the top 2–3 cm of RMB asphalt concrete. The ideal RMB would have pre-irradiation properties similar to existing bitumen binders, enabling a “drop in” technology that does not influence current road construction equipment or techniques.

The cost of the bitumen binder in asphalt is a very small fraction of the roadway cost, thereby allowing the RMB to cost significantly more without substantially increasing the overall cost per lane mile. The reason to use a high-power, high-energy, mobile electron beam accelerator for in-situ modification of roadway surfaces built with RMB is to extend the lifetime of asphalt roads. Fermilab has applied for a patent on this technology. An illustration of the planned mobile, high-power electron accelerator is shown in Figure 2-2.

This technology seeks to substantially reduce the energy wasted each year to constantly resurface asphalt highways. Extended life asphalt will reduce the fuel usage and carbon footprint of heavy machinery for road repair; decrease energy used for hot mix asphalt; reduce fuel use due to traffic congestion caused by asphalt highway repairs; and result in substantial saving of taxpayer dollars.

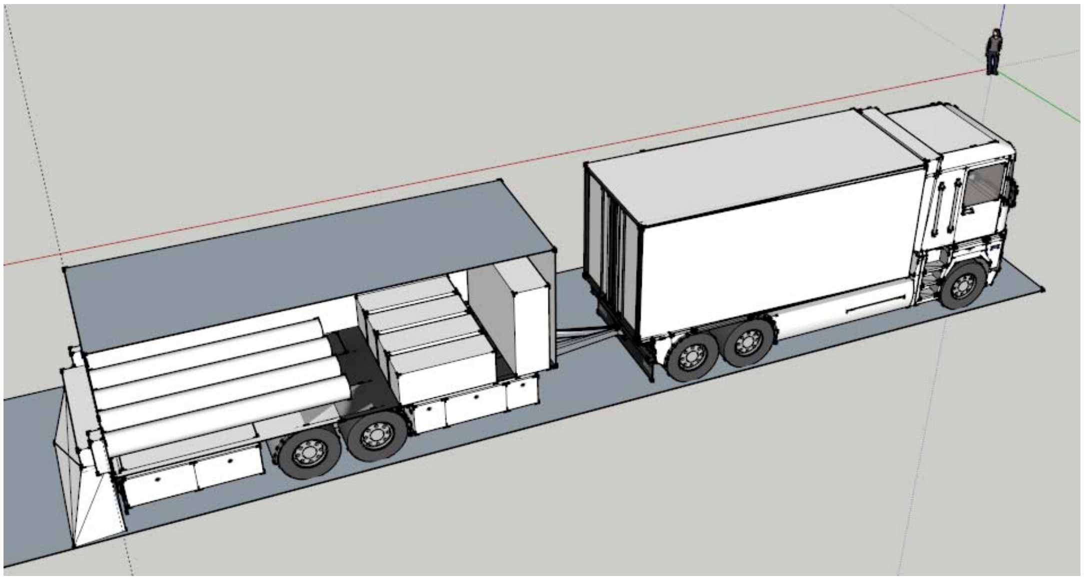

Figure 2-2 Illustration of a mobile, high-power electron accelerator to drive reaction chemistry in roads.

How is asphalt concrete made today? Asphalt concrete is made and modified in a mixing plant. Because of the high molecular weight distribution of bitumen, it is very viscous at room temperature and is typically heated to between 130° and 150°C and mixed with aggregate. Chemical reactions take place upon heating such that the hot mix asphalt concrete mixture has a finite lifetime. This partially explains why there are on the order of 10,000 asphalt mixing facilities in the U.S. Such plants have both large energy requirements and significant emissions. Much effort has been devoted to developing binders that can be handled at lower temperatures (warm-mix over hot-mix) to reduce energy costs and pollution from the road construction process. Current additives, like rubber, actually make processing of the hot mix more difficult, limiting the amount of additive that can be used and thus its effectiveness. The workable lifetime of the asphalt concrete is especially an issue in colder climates. If successful, the resulting technology will significantly extend the lifetime of asphalt highways, resulting in large energy and taxpayer savings. While project goals are more ambitious, even a 1-yr extension in the service lifetime of highways will have a huge impact on the carbon footprint of this industry and result in substantial savings in lifetime costs of asphalt highways.

2.7.2 Regulatory Framework (Q2)

Cross-linking and polymerization of plastics with accelerators is a well-established industrial process. Regulations for irradiation of materials follow guidelines established by the International Atomic Energy Agency (IAEA). These guidelines limit the energy of electron beams to 10 MeV or less to avoid creation of neutrons, leading to activation of materials being irradiated. Simulations of a 10 MeV electron beam with normal incidence on an asphalt road surface have shown that exposures of ~ 200 kGy can be achieved with >2 cm penetration for the electrons, with an additional >1 cm due to the X-rays produced while maintaining peak temperatures in the asphalt below the flash point of bitumen. Many materials can be cross-linked with <200 kGy, so this should be considered an upper limit on the needed dose. With this dose we have demonstrated by simulation that the required ground-following shielding (the radiation safety barrier) can be designed such that nearby workers are not exposed to radiation levels beyond those allowed by current U.S. regulations.

2.7.3 Economic Analysis (Q3)

Relative road construction and maintenance costs vary greatly depending on the location, labor cost, and climate. The cost to grind and resurface an asphalt road varies between \$0.6M/lane-mile for rural roads to \$4.0M or more per lane-mile in urban multilane roads. The cost to rebuild an asphalt road starting with a fresh base is substantially higher. It is estimated that the RMB process will add roughly \$14k per lane-mile of road, making it highly cost effective even if the process provides only a 10% life extension between resurfacings.

Natural strategic partners for this development effort are accelerator manufacturers, heavy equipment builders, and large petro-chemical companies, who will be the ultimate suppliers of the required equipment and binders. A small-scale demonstration of the technique, for example, on the site of a national laboratory, will encourage large-scale investments. Demonstration of a mobile accelerator and RMB process with well understood costs and benefits is a key step to first use on public highways.

2.7.4 Performance Criteria (Q3)

In-situ modification of a road surface will require 100–200 kGy of delivered dose via an electron beam of approximately 10 MeV. To achieve one or two lane miles per 8 hr shift, the mobile accelerator envisioned is required to deliver a total of ~1.4 MW and should fit in the envelope of a typical trailer truck. It must also be highly reliable with built-in redundancy. The format envisioned contains four accelerators of 500 kW each, with overlapping magnetically swept beams such that the device is still operational even with one accelerator down. Standard, commercial generators with trailer-mounted gas turbines provide the electrical power and are readily available in the 2–3 MW range. The vision is a standard commercial semi-truck providing motive power, a first trailer providing electrical generation, and a following custom trailer containing the accelerators, RF power source, and cooling systems. The accelerator trailer will be equipped with ground-following shielding to ensure doses are acceptable for nearby workers. Preliminary estimates of the accelerator, RF power, and shielding indicate acceptable overall weights for standard over the road transport of the equipment from site to site.

2.7.5 Technical Gaps (Q4)

Technical gaps in this technology include the following:

- Development and demonstration of light, robust electron accelerators in the 500 kW power range for mobile applications
- Development of efficient and cost-effective RF power sources
- Development of robust and simple electron guns
- Development of simple turn-key accelerator control and operating systems
- Development of in-situ dose measurement and feedback systems (similar to medical accelerators)
- Development of ground following shielding with integrated active radiation interlocks to protect workers

- Development and testing of cost-effective modified bitumen or alternative binders that allow drop in use with existing asphalt highway construction equipment, polymerize with < 200 kGy, and result in improved mechanical performance, toughness, and low-temperature cracking performance compared to bitumen

2.7.6 Synergistic Application-Side R&D (Q5)

In-situ modification of materials via electron beam processing is a largely untapped field that has unique advantages over traditional methods in which material properties are unchanged from application to use.

2.7.7 Required R&D to Bridge Technical Gaps (Q6)

A first step is to identify useful bitumen additives or alternative RMBs that can be treated with an electron beam to custom tailor the properties of the roadways through cross-linking. A second objective is to design the required mobile accelerator, including power sources, cooling, and shielding.

A key challenge is identifying a suitable RMB. It is known that electron beam interaction with the neat bitumen can either (i) cause cross-linking of the hydrocarbon chains leading to a higher average molecular weight or (ii) bond cleavage leading to a lower average molecular weight. Preliminary work has shown that electron beam treatment at the level of 200 kGy does not further cross link standard bitumen used for roads. However, many possible additives to bitumen could be cross-linked via an electron beam. Also, non-asphaltene materials are candidates for use as the base material for the RMB. As mentioned earlier, a viable RMB can cost much more than bitumen without having a large impact on road construction costs.

Another potential challenge is that viable RMBs may not behave like bitumen when heated, preventing a “drop in solution.” Current modification to bitumen binder to improve roadway lifetime is fundamentally limited by bitumen viscosity and fabrication of the asphalt concrete in a plant often far from the point of use. By chemical modification of the asphalt concrete after the road is installed via an electron beam, the properties of the RMB can be tailored to the needs of the road construction as well as those demanded by climate and road use.

A third challenge is building the required industrial accelerator at acceptable costs. While designs for linear accelerators are well understood, this accelerator presents new challenges because it must operate reliably in continuous wave (CW) mode with high efficiency. It must also be lightweight and compact (so it can be shielded effectively), and have a ground-hugging flexible radiation shield that must adapt to the contour of the road to prevent electrons and X-rays from irradiating workers. The accelerator must also employ a simple turn-key operating system that can be handled by non-experts and is highly reliable.

2.7.8 Barriers to Commercialization and Technology Introduction (Q6)

Construction of asphalt and concrete highways is a well-established and conservative industry. It is closely tied to both the political system and to organized labor. Construction projects are largely funded with public funds, which are conservative by nature. Current funding models focus on project cost vs. cost of ownership models. However, the FHWA and many State Department of Transportation (DOT) offices are moving to a total cost model, which would favor this technology. Extending highway lifetimes will reduce the labor required to repair them. It will be important to argue the benefits of using the current workforce and funding to achieve better national highway infrastructure vs. simply cutting jobs. Public acceptance of a new technology involving irradiation will require a program of education for decision makers, highway workers, and the general public. None of these barriers seems to be insurmountable.

2.7.9 Roadmap for Development (Q7)

At present, the technology suitable for asphalt curing does not exist. A significant amount of research related to bitumen and additives is still needed. A project that is jump started to achieve the basic demonstrations will attract significant private investment from strategic partners. Ultimately, the team that drives this technique to commercialization will most likely be a partnership of government labs and large strategic industrial equipment and chemical companies. This technology is expected to be transformational, fundamentally altering the way U.S. highways are built. An education and information program will be required to explain the opportunity to key stakeholders.

2.8 Emerging Issues

2.8.1 Emergency and Disaster Response

In 2014 there was a chemical spill in West Virginia, Elk River, of methyl cyclohexane methanol and several other chemicals. As a result of the intake of this water to the water treatment plant, approximately 15% of the population of West Virginia was warned “do not use” the water [2-34]. This warning meant that the population should not drink the water or use it for cooking or even bathing/showering. In this case, a mobile electron beam system could have been deployed to provide a treated drinking water for emergency consumption. Because of the locally widespread delivery of contaminated water (over seven counties), distributed water centers were established to meet the needs of the local population.

2.8.2 Electron Beam Systems for Developing Countries

Many countries have eliminated the need for extensive telephone infrastructure by going from no telephone directly to cell phone technology. In a similar manner, it is possible that underdeveloped countries, with no existing infrastructure for purifying water and treating wastewater, may find electron beam technology an economic next step. This technology could be phased in so that the top priority issues are addressed at first and, as the societal pressures build, additional components could be added. Electron beams are capable of providing disinfected water in one single process. No halogenated disinfection by-products are produced, and the water could be consumed with minimal bacterial and viral infection.

2.8.3 Treatment of Reverse Osmosis Reject (Retentate) Water

One of the treatment processes being used in several coastal water treatment plants is reverse osmosis. This is economical because the reject water (the water that does not go through the membrane) is returned to the wastewater treatment plant and disposed (one possibility being ocean discharge). Where there is no option for disposal of the reject water, it will have to be treated to reduce the concentration of pharmaceutical and other personal care products as well as other emerging compounds. Electron beam treatment presents a potentially cost-effective process to remove these organic compounds and allow disposal in natural water [2-35].

2.8.4 Ebola and Other Emerging Diseases

The recent case of Ebola in Dallas, Texas, brought in from West Africa, alerted the country to a threat that previously was a non-issue in the U.S. It was very rapidly realized that no data were available on the survivability of the virus in wastewater or drinking water, understanding was lacking on the potential of aerosolization in a wastewater treatment plant, or bathrooms either in the home or public facilities. Also, no data were available to determine the necessary disinfection regimen for public wastewater and water treatment plants. Electron beams provide a general-purpose tool for disinfection that could be effective against a wide array of such threats.

2.8.5 Water Treatment for Remotely Deployed Personnel

West Africa is an example of where a mobile unit could be helpful. In regions where there are outbreaks of hemorrhagic fever, mobile units could be deployed to treat water for drinking and for health care. Another example where such units could have been used is the earthquake in Haiti, where surgeons had no water and they were relegated to using hand washing for hygiene.

2.8.6 Accidental Chemical Contamination of Surface Waters

Recently 1,4-dioxane was found in the Cape Fear River, and studies are underway to try to determine the source and the extent of the pollution [2-36]. This pollution is likely only the tip of the iceberg as far as either accidental spills or discharges of unregulated organic compounds. Because of the versatility of the electron beam process as time progresses, there may be situations where it can be utilized on either a temporary or permanent basis. Since chemical decontamination requires relatively high doses, mobile or portable high energy electron beam technologies are needed.

2.9 Overview of Accelerator Systems for E&E Applications

As outlined above, in many areas accelerator applications in energy and the environment require advances in accelerator technology beyond today's state of the art. While the commercially available capabilities serve well the industrial sector for electron beam processing, E&E applications demand higher beam power but at costs that will make them competitive with non-accelerator technologies.

The landscape of application-pull and technology-push, shown in Figure 2-3, is a complicated one. The application pull demands higher beam power at lower cost. The technologies that are appropriate for these applications divide generally into electrostatic DC accelerators and RF-driven accelerators. Technology gaps are both system-specific and broadly applicable, as shown in Figure 2-3.

These many potential applications demand development of a set of accelerator technology capabilities that go beyond today's state of the art. Table 2-11 outlines a set of core accelerator capabilities and performance targets for different applications. Meeting any one of these capabilities opens up E&E applications to accelerator technology in ways that go significantly beyond what is possible today. Two entries in the table, the medium-scale, low-energy (1 MW) system and the large-scale, high-energy (10 MW) system represent approximately one order of magnitude improvements beyond the capabilities available today.

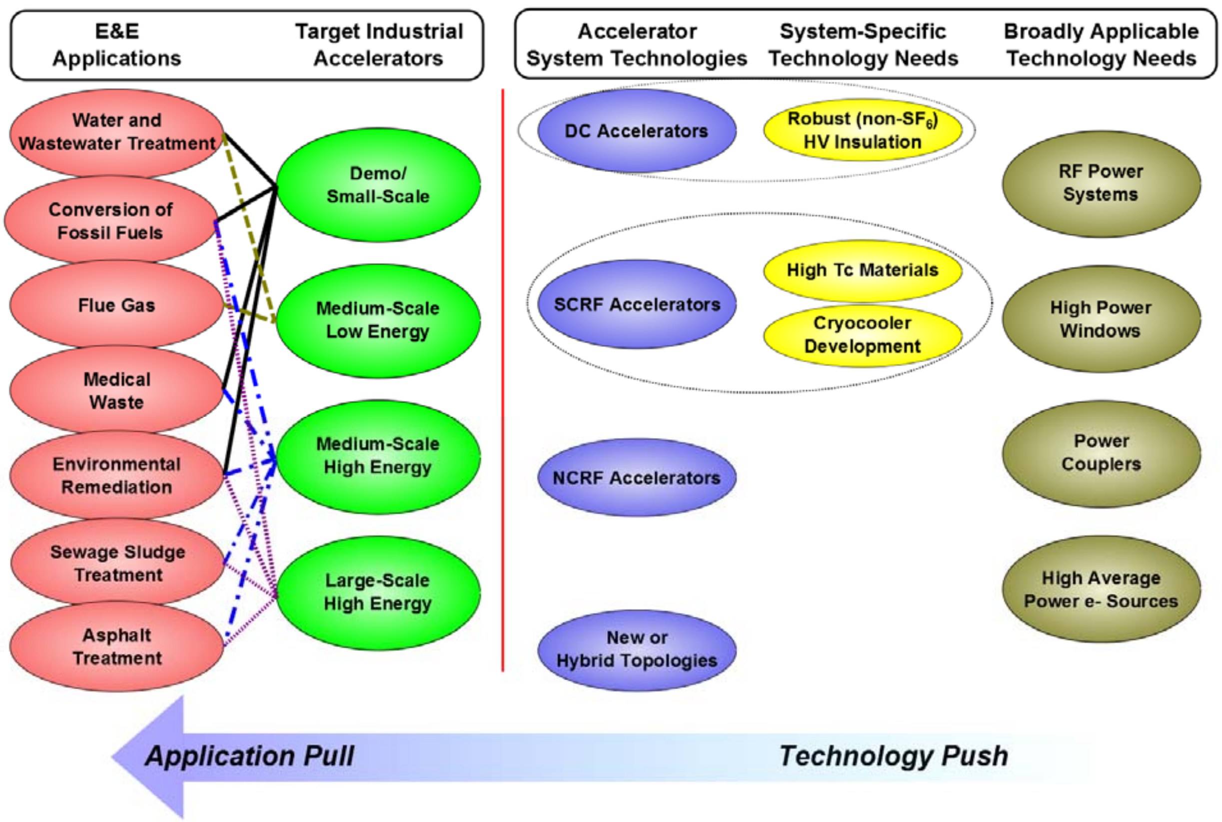

Figure 2-3 Accelerator applications in E&E require capabilities beyond today's state of the art. Candidate technologies require R&D to fill capability gaps; much of the R&D is broadly applicable across potential technologies.

The remainder of this chapter addresses charge questions 4, 6 and 7, which cover the technical gaps in the present state-of-the-art of electron-beam accelerator technology and the required R&D activities needed to bridge those gaps.

The accelerator capability targets shown in Table 2-11 meet the application needs shown in Figure 2-4.

Table 2-11 Core accelerator capabilities and performance targets.

	Demo/ Small Scale	**Medium Scale Low Energy**	**Medium Scale High Energy**	**Large Scale High Energy**
Description	Demo and pilot-scale low-energy systems	MW-class, industrial-scale, low-energy systems based on DC technology	MW-class, industrial-scale, high-energy systems	10 MW-class, industrial-scale systems based on RF technology
Applicability to E&E Needs	Sterilization, R&D	Flue gas, wastewater	Wastewater, sludge, medical waste	Wastewater, sludge, medical waste
Electron Beam Energy	0.5–1.5 MeV	1–2 MeV	10 MeV	10 MeV
Electron Beam Power	>0.5 MW	>1 MW	>1 MW	>10 MW
Electron Beam Current	0.33–1.0 A	0.5–1.0 A	0.1 A	1 A
Target Capital Costs	<$10/W	<$10/W	<$10/W	<$5/W
Target Electrical Efficiency	> 50%	> 50%	> 50%	>75%
Size Constraints	None	Some applications require portability	Some applications require portability	Compact designs drive down overall CAPEX since shielded enclosures are major expense

		Energy and environment applications						
		Wastewater	Sludge	Flue Gas	Medical waste	Environmental Remediation	Asphalt treatment	Emerging applications
Capabilities	Demo/pilot scale 0.5 MW; 0.5-1.5 MeV	1	2	2	1	1	3	1
Capabilities	MW-class DC system 1 MW; 1-2 MeV	1	2	1	2	2	2	1
Capabilities	MW-class high-energy 1 MW; 10 MeV	2	1	3	1	1	1	1
Capabilities	Ten MW-class high-energy 10 MW; 10 MeV	2	1	3	3	1	1	1

1	Very important
2	Somewhat important
3	Not important or not applicable

Figure 2-4 Mapping of accelerator capabilities explored in this chapter to application needs.

2.10 Relevant Accelerator Systems

Accelerators and accelerator technology are in use in thousands of applications today. These applications include ion implantation for electronics and materials science, production of medical isotopes and radiation therapy, bulk irradiation for sterilization and pathogen destruction, polymer cross-linking of electrical wire insulation, and fabrication of radial tires and other materials. The vast majority of these use low energy (<1 MeV) and/or low power (<100 kW) accelerators from designs that are decades old. There are a few higher power applications (100's of kilowatts), but those designs are of similar vintage.

Figure 2-5 shows the range of current industrial accelerators in use in industry and medicine today. (The medical values are included to give a reference to accelerator applications commonly known in the general population.) However, most large-scale future uses are envisioned to be electron beam accelerators with beam powers of greater than 0.5 MW and energies of 1–10 MeV. Beams of this energy can be used to irradiate a product without activating it, and they eliminate activation issues for the accelerator and its environment (beam off – radiation off). Table 2-12 shows a representative set of commercially available accelerators in the energy range of 1–10 MeV.

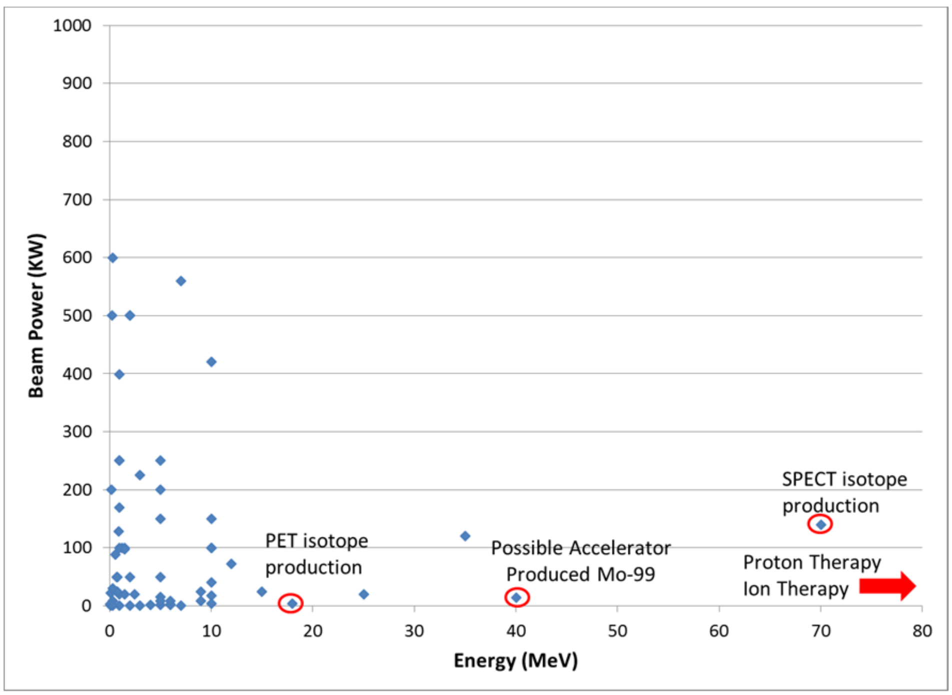

Figure 2-5 Survey of beam energy and beam power of industrial accelerators in use at present. Well known medical applications of accelerators shown as reference.

All of the machines in Table 2-12 represent the maximum output that their designs can produce. New designs incorporating modern accelerator technology are needed that will allow scaling to higher beam powers, up to and beyond 1 MW. The accelerators described below use RF cavity-based designs but with modest currents and again do not incorporate the latest developments to produce high power beams.

Varian Medical uses its expertise in the development and production of medical electron accelerators for its Linatron line of industrial RF cavity-based accelerators. These can produce up to 15 MeV electron beams but only about 25 kW of beam power. Similarly, Mevex of Canada produces RF cavity-based accelerators with beam powers of 100 kW or less. Most other accelerators in the plot are used in lower energy and power applications, such as cross-linking of wire insulation and other surface treatments where the electrons do not need to penetrate very far into a surface.

Table 2-12 Representative commercially available electron-beam accelerator technology.

Manufacturer	Model	Type	Beam Energy (MeV)	Beam Power (kW)	Electrical Efficiency	Approximate Cost*
NIIEFA	UEL-10-D	RF-Linac	10	10		
NIIEFA	Elektron 23	DC	1	250	90 %	$2M
BINP	ILU-10	RF-SCR	5	50	20–30 %	$3.6M
BINP	ILU-14	RF-Linac	10	100	26 %	$5.1M
BINP	ELV-12	DC	1	400	95 %	$2 M
IBA	Dynamitron	DC	5	300	30–60 %	$4.9M
IBA	Rhodotron	RF-SCR	7	560	55 %	$8M
NHV		DC	5	150		$5M
L3	Sureβeam	RF-Linac	10	150	10–20 %	
Varian	Linatron	RF-Linac	9	25	10–20 %	$1M
Mevex	Linac	RF-Linac	3	3		
Wasik Assoc.	ICT	DC	3	10		
Getinge Group	Linac	RF-Linac	10	20		
Vivirad S.A.	ICT	DC	5	20		

* Costs are approximate and for illustrative purposes only. They were obtained from the available literature and may not represent current prices.

NIIEFA – Efremov Institute, St. Petersburg, Russia
BINP – Budker Institute for Nuclear Physics, Novosibirsk, Russia
IBA – Ion Beam Applications, Belgium
L3 – L3 Communications, USA
Varian – Varian Medical Systems, Security & Inspection Products, USA
Mevex – Mevex Corporation, Canada
SCR – Single Cavity Resonator

It is evident in looking at the plot that present accelerator technology rarely can produce more than 0.5 MW of beam power. Accelerator technology in industrial uses today does not take full advantage of the technology being developed in the world's accelerator physics and engineering laboratories. Most use technology that is many decades old. Very few use cavity-based accelerators and those that do tend to be low current and, therefore, low beam power. Superconducting RF technology, which can enable CW operation with both high beam power and good wall-plug power efficiency, is just beginning to find its way into future industrial accelerators but will require R&D efforts to simplify systems and lower costs.

New applications that are described in this report will utilize radiation-driven chemistry in which electron beams impart large quantities of energy into bulk quantities of materials to stimulate chemical reactions on a macroscopic scale. On the one hand, pushing the capabilities of accelerators to higher levels will require further development of accelerator technology. On the other hand, engagement with the industrial community is required to develop and demonstrate the applications leading to deployment of new accelerator technology in the high power regime.

2.10.1 DC Accelerator Systems

Technology Description

Most commercial accelerators in use today, particularly the higher power applications, use a charging system that converts an AC current into a DC voltage. The charging or rectification system and the accelerating column are generally contained in a pressure vessel filled with an insulating gas such as sulfur hexafluoride, resulting in large physical sizes and large radiation enclosures. The DC voltage is applied to an accelerating column, which is used to accelerate the electrons from an electron source at high potential to ground. In applications that irradiate large objects, a window is required between the vacuum of the accelerating column and the ambient environment. Generally, a beam sweeping system is used to both spread the beam over the object being irradiated and to distribute the energy absorbed in the window. Overviews of DC accelerator systems are given in Refs. [2-37, 2-38].

High-power, high-voltage DC accelerators have the following features:

1. The efficiency is very high, 85–92%, which is determined mainly by the frequency converter [2-39, 2-40].
2. The acceleration gradient is limited by high-voltage breakdown in the acceleration tube, in the presence of high-power beam. Beam loading may significantly change the field distribution along the acceleration tube during the breakdown, and cause the total breakdown of the tube. A total breakdown can potentially damage the accelerator, and should be limited to not more than once a year for around-the-clock operation. Typical gradients are 0.8–1 MeV/m in the accelerating column. Due to the large physical size of the pressure containment vessel, the effective gradients are lower.
3. The beam energy is limited by the energy stored in the accelerator and, especially, its extraction efficiency during breakdown. Presently, the typical value for reliable and safe CW operation is <3 MeV.
4. The power is limited by beam losses, such as the beam halo, which for reliable operation should be at the level of a few microamperes. Presently, the beam current is limited to 1 A. Increasing the beam power requires meticulous optimization of the acceleration tube optics to minimize the beam losses.
5. Another beam power limitation is the beam extraction system—either a raster window with air-cooled titanium foil or differential pumping. Probably, reliable extraction of a 1 MW beam is feasible. If a window is used, the beam power is limited by the ionization losses in the window foil For a differential pumping system, the beam is extracted

through a system of holes with few mm diameter, and the power density should be smaller than 10 MW/cm^2 [2-39]. Note that in this case the beam energy stability should be better than 2–3 % [2-39].

Example Relevant Existing Systems

In Russia, both the Budker Institute in Novosibirsk and the Efremov Institute in St. Petersburg produce accelerators for industrial applications. They are used throughout the former Soviet Union and China. All of their designs are transformer-based DC accelerators. Maximum power for reliable operation appears to be less than 500 kW, and most models are 1 MeV or less. Reports on applications for electron-beam flue gas treatment and water treatment, where attempts were made to increase the power to ~800 kW, indicate that reliability has suffered in this effort. The Budker Institute produces the ILU and ELV lines of accelerators. The Efremov Institute produces the UEL and "Electron-x" lines of accelerators. The cost of a 400 kW ELV is approximately $2M.

As an example, the ELV-12 uses three accelerating columns powered from a single high-voltage source. The three columns are used in parallel to provide a beam with up to 1 MeV, 133 kW beam each for a total of 400 kW. Each of the three outlets has its own scanning system and vacuum window. Most of these accelerators are used for plastics modification and sterilization applications. Some, however, have been used in electron beam flue gas treatment and wastewater treatment.

The insulating core transformer of the High-Voltage Engineering Corporation is based on insulated secondary windings that are rectified and series-stacked to achieve high voltage. These accelerators operate in the range of 0.3–3 MeV and have achieved beam power up to 100 kW.

IBA in Belgium produces the high-frequency-AC-driven DC accelerator called the Dynamitron. Dynamitrons were developed in the 1960s and can create beams up to 5 MeV and 250 kW.

State-of-the-Art System Performance

State-of-the-art DC accelerator systems provide approximately 0.1 MW (from 1 MeV electron beams x 100 mA) per single electron column (Table 2-13). Example systems include the Dynamitron (150 kW beam power at 3 MeV), the ICT (100 kW beam power at 3 MeV) and the ELV (up to 100 kW at ~1 MeV). Higher power can be achieved by grouping several of the columns together, as the ELV-12 does to achieve 400 kW total in three columns. The wall-plug to electron-beam efficiency seen in the DC accelerator is very high, greater than 60%.

DC Accelerator System Technology Gaps

Table 2-11 presents parameters for a DC-based, MW-class, industrial-scale accelerator system. Such a system requires 1–2 MeV beams with 0.5 to 1 A beam current, representing an order-of-magnitude leap in beam power capability relative to present technology. Limitations arise from 1) beam loss in the accelerating column that leads ultimately to high-voltage (HV) breakdown, 2) low beam-window power density, and 3) reliability problems with high power operation of high voltage systems. In addition, the use of the insulating gas SF_6, which is common in DC accelerator systems to achieve good high-voltage standoff performance, is becoming increasingly problematic as SF_6 is an extremely potent greenhouse gas. Therefore, alternatives may be required in the future.

These needs motivate R&D to:

- Improve the reliability aspects of high voltage and power conversion systems.
- Develop solutions for SF6-free operation.
- Improve beam power handling of window systems and develop windowless approaches.
- Develop approaches for handling very high DC beam currents in accelerating columns.

Table 2-13 Present DC accelerator characteristics in the context of E&E systems.

	Present Performance	**Note**	**Citation**
	Metric 1: Electron Beam Power		
Accelerator	400 kW @ 1 MeV in 3 columns (133 kW each)	Achieved with ELV-12	[2-41]
Window	>500 kW	100s – 1000s of hours depending on environment on non-vacuum side	[2-42, 2-43]
Electron Gun	>100 mA	Not limiting factor	
	Metric 2: Capital Costs		
Total System	Example 1: $5/W	ELV-12	
	Metric 3: Operating Costs		
Accelerator Power	50–60% efficient	Measured from AC mains to electron beam output. Includes all sub-systems	[2-44, 2-45]

2.10.2 Normal Conducting RF Accelerator Systems

Technology Description

Normal-conducting RF (NCRF) accelerator systems include the following components:

- Injection system. Generates the high-current bunched beam for the NCRF structure. The injection system may be external, containing, for example, a gridded gun with a thermionic cathode, accelerating the HV gap, and focusing elements, or it may be built into the RF cavity. In either case, DC bias and RF voltage (harmonic of the operating frequency) are applied to the cathode in order to form a short bunch.
- NCRF accelerating structure. High-power CW industrial accelerators use room-temperature RF cavities that are typically a single-cell RF cavity or standing-wave multi-cell cavities. The aperture of the RF structure should be large enough to avoid unacceptable beam current interception (and achieve sufficient RF field flatness in the case of multi-cell cavity), but small enough to provide reasonable surface field and R/Q

(ratio of shunt impedance to quality factor). The complete system includes cooling, frequency tuner, pumping, supports, etc. The main requirements for the high-power NCRF structure are efficiency, longevity, and reliability.

- RF source. This critical part of the accelerator system is a significant cost driver. In the CW regime, 1 MW-class, RF sources are typically gridded tubes, klystrons, tetrodes, and inductive output tubes (IOTs), albeit at lower power. The main requirements for the RF sources are described elsewhere.
- Beam extraction system. This is that same as for the DC accelerator (see Section 2.10.1)

The NCRF accelerator efficiency is determined by the efficiency of the RF source and the NCRF structures. The efficiency of the present RF sources is in the range of 30-65%, depending on the tube type. Linac structure efficiency is determined by the ohmic losses in the cavity walls.
Below are some of the ways that ohmic losses have been reduced in the past:

- Reduce acceleration gradient, thus increasing the linac length (ILU-14). Drawbacks to this approach are potential issues with the beam current interception and, of course, compactness.
- Use the pulsed regime. In this case, the RF power should be increased and, thus, the cost of RF. In addition, there may be problems with the beam current interception caused by space charge issues.
- Accelerate the beam many times in the same cavity (e.g., Rhodotron or racetrack microtron). In this case, there may be the issues with the beam current interception in the dipole magnets.

In the future, it should be possible to achieve high efficiency (85–90%) of the NCRF cavity at the power level of 1 MW and the beam energy up to 10 MeV with a properly optimized system. To attain this goal, the ohmic losses (power dissipated in the structure walls) should be kept low (<100–150 kW) in fully beam loaded operation.

Given the structure input power P (in W), accelerated beam voltage U (in V), length L (in m) and frequency f (in MHz), the ohmic losses in the walls are:

$$P_w = \frac{U^2}{\frac{R}{Q} * \left(\frac{L}{0.309}\right) * \left(\frac{f}{325}\right) * Q_0 * \sqrt{\frac{325}{f}}}$$

while the remainder of the power is delivered to the beam, $P_b = P - P_w$. Efficiency η is:

$$\eta = \frac{1}{1+P/P_b}\,.$$

Efficiency versus length for different frequencies is shown in Figures 2-6 and 2-7 for 10 MeV beam energy and both 1 MW and 10 MW beam power. As the figures show, high efficiency is achievable. For a 10 MW design, at 1.3 GHz, the RF-beam efficiency would be 98.9%, resulting in 110 kW dissipated over an accelerator length of 10m. This would result in a heat loss per accelerator length of 11 kW/m. For the cavity with the drift tubes taken as an example

(Table 2-14), the peak surface ohmic losses may achieve 10 W/cm^2, which may require special means for cooling.

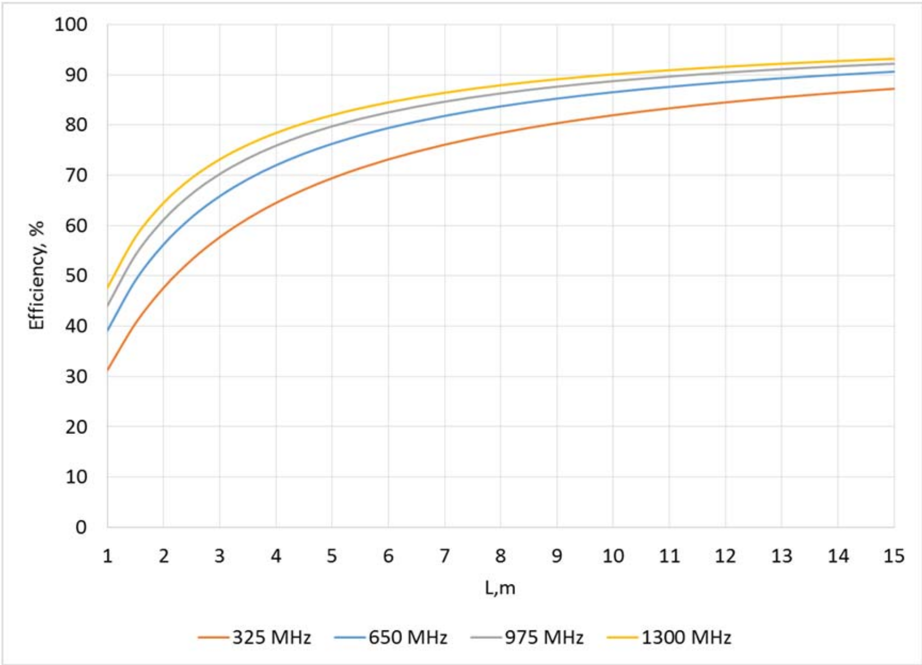

Figure 2-6 Efficiency versus the linac length for different frequencies for 10 MeV, 1 MW linac. Efficiency is ~90% for the ~10-m long linac at 1300 MHz.

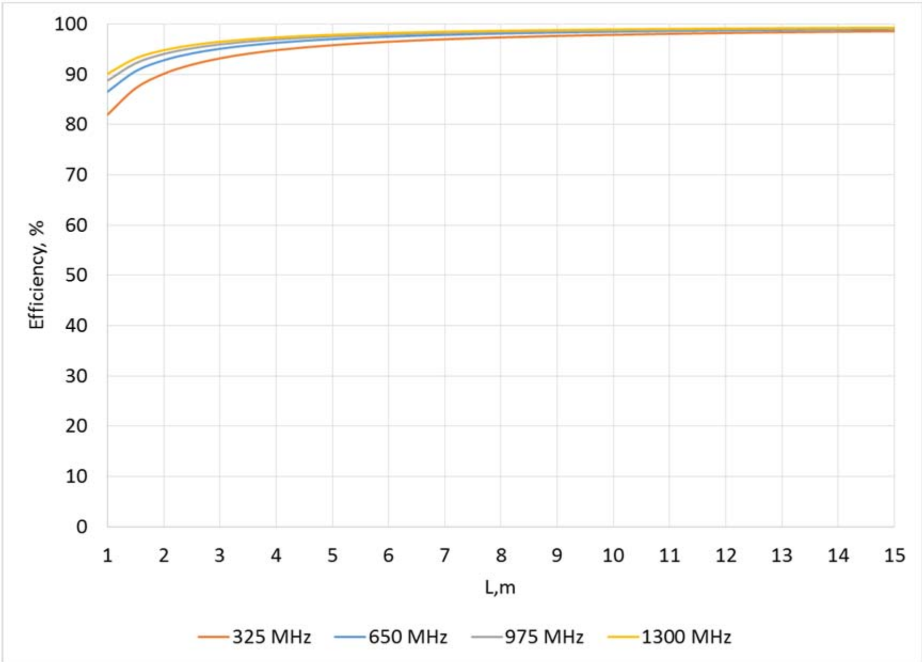

Figure 2-7 Efficiency versus the linac length for different frequencies for 10 MeV, 10 MW linac. The efficiency is not an issue, but power losses on the cavity wall may be critical.

Table 2.14 Example of the 10 MeV, 1 MW CW linac efficiency.

	Unit	
Operating frequency, f_0	MHz	325
R/Q	Ω	340.8
R_{sh}	M Ω	14.05
Unloaded cavity quality factor, Q_0	Q_0	41200
Accelerator aperture	mm	70
Cavity length, L_0	mm	309

Example Relevant Existing Systems

IBA in Belgium produces the Rhodotron, a CW electron beam accelerator combining high power and high energy. The Rhodotron is an RF-based accelerator with a large central cavity that is traversed multiple times by the electron beam. Each time the beam traverses the radius of the cavity, it gains kinetic energy. The Rhodotron can provide one or several beam outputs from 2 to 10 MeV. The highest power model provides 7 MeV output energy and is designed to operate at 700 kW, having demonstrated that performance in a short test. It operates routinely at 560 kW in commercial application. The 7 MeV Rhodotron costs approximately $8M.

State-of-the-Art System Performance

Table 2-15 summarizes the present performance for NCRF accelerators.

Table 2-15 Present NCRF accelerator characteristics in context of E&E systems.

	Present Performance	**Note**	**Citation**
	Metric 1: Electron Beam Power		
Accelerating Structure	State of the art: 700 kW (7 MeV at 100 mA)	State of the art Efficiency = 55 %	[IBA website]
Window	Same as DC accelerator	See Table 2-13	
Electron Gun	Variable current from few μA to mA's	Limited to 100 mA	
RF Power System	Tetrodes at 100 MHz; Diacrode at 200 MHz; Klystron at 350–3000 MHz; IOT	Few RF sources can produce power on the 1 MW scale	
	Metric 2: Capital Costs		
RF Power System	$4/Watt	Estimate	
Accelerator Cavities	$2–3/Watt	Estimate	
Total System	$11/Watt	Estimate	
	Metric 3: Operating Costs		
RF Power	40–60% wall-to-RF efficiency		
Accelerator Cavities	>90%		
System	>55%		

NCRF System Technology Gaps

Future NCRF accelerator designs should be optimized for low energy (1–10 MeV), high current (1-A scale), and high RF-to-beam efficiency (85%). Beam loss and stray particles (halo) will be a concern at high power. Modeling will be important in the design of the electron transport from the source and through the accelerating structures. All supporting systems are also needed, such as high-power RF windows and couplers. The final goal will be a system-level demonstration with capital cost of the NCRF linac <$3–4/W.

2.10.3 Superconducting RF (SRF) Accelerator Systems

Technology Description

While essentially all commercial and industrial RF accelerators rely on proven normal-conducting technology, the development of superconducting RF (SRF) technology in the national labs and universities is making its way into the commercial world. Early adopters will be high value applications such as isotope production, lithography, and small mobile systems for security and cargo scanning applications or for replacement of industrial radioactive sources.

A superconducting linac operates in very much the same way as a room temperature one, but with a few key differences. The first and most obvious is that the accelerating cavities are cryogenically cooled to 4 K or below, resulting in very low wall losses and, potentially, higher CW gradients. The cavities must be housed in a vacuum-insulated cryostat and must be continuously cooled by some form of cryogenic system. The cost of the cryogenic systems is a significant fraction of the total cost such that there is a great premium on increasing the SRF cavity quality factor (Q_0) and operating temperature. Currently, the capital cost of SRF-based linacs is higher than that of normal-conducting linacs. However, since the accelerators may be more compact, the size of the shielded enclosure can be smaller, especially compared to DC machines, limiting overall capital costs.

The cavity coupling is set to deliver essentially all the RF power to the beam at maximum current so that the operating efficiency can be very high, even if the practical efficiency of the cryogenic system is taken into consideration. Thus, operating costs may be lower than those for a normal-conducting machine, especially if the system is constructed with high Q_0 cavities and designed for low cryogenic losses. Therefore, RF source efficiency is the major remaining factor in total operating costs. The SRF cavities may have an advantage due to potentially larger beam apertures compared to copper ones; however, they are very sensitive to beam losses, since even a small intercepted current represents a large heat load. Also, SRF cavities are very sensitive to contamination from the vacuum system and must be carefully protected during assembly, transport, and operation. All these factors must be carefully considered in the detailed design of any system.

A practical advantage of SRF over NCRF linac accelerator systems is that their BCS cavity losses are insignificant when compared to the resistive losses of copper accelerating structures. This means that almost all the expensive RF power that is directed into the accelerator is used to accelerate the beam and maximize the wall-plug efficiency of the acceleration process. In addition to the inherent wall-plug efficiency reduction, high-power NCRF accelerators require significant water-cooling systems to remove the waste heat, further reducing the efficiency.

Unfortunately, SRF systems give up some of their advantage by requiring the use of complex, expensive, and inefficient 2 K cryogenic refrigeration plants to cool the structures to liquid helium temperatures. The penalty can be greatly reduced by utilizing high Q_0 cavity structures that can operate at 4 K rather than 2 K, where the cryoplant requirements and expense are significantly reduced, since the cryogenic capacity of a plant at 2 K is less than one-third that at 4 K. Recent improvements in cavity Q_0 for pure niobium 1300 MHz cavities at Fermilab and demonstrations at Cornell University of $Q_0 \sim 2 \times 10^{10}$ at 4 K (in 1300 MHz nine-cell elliptical cavities coated with Nb_3Sn) hold great promise for smaller, less expensive, and less complex SRF industrial accelerators. The recent availability of high power (~ 5 W at 4 K) cryocoolers and the development of conduction-cooled cavities also can enable use of SRF for small, simple, turn-key industrial accelerators for a host of new applications.

SRF systems are particularly suited to high power applications. One reason is that the fixed costs for the accelerating structures and the cryoplant do not scale with beam current, and hence, the higher the beam current that can be driven at a given delivered energy, the higher the wall-plug efficiency and, in turn, operating expense (OPEX) savings, as well as the reduced CAPEX that can be achieved. When driven with high-efficiency RF sources, high system wall-plug efficiencies, potentially as high as 75% may be possible, rivaling DC systems.

Example Relevant Existing Systems

Examples of large SRF systems include the Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab (12 GeV, 1 MW electron beam), the Spallation Neutron Source at Oak Ridge (1 GeV, 1 MW proton beam, pulsed), and machines under construction such as the X-ray Free Electron Light Source (XFEL) and European Synchrotron Source (ESS) in Europe and Linac Coherent Light Source (LCLS-II) in the U.S. These are generally high-gradient, low- or modest-current machines. In storage rings such as KEK-B and Cornell Electron-positron Storage Ring (CESR), modest gradient but high-current (ampere class) systems have been proven, along with MW-class RF systems and RF power couplers, demonstrating that SRF-based systems are capable of accelerating ampere-class beams, albeit in a regime appropriate for particle colliders. Smaller systems are under active development, such as the Cornell University Energy Recovery Linac (ERL), machines for isotope production, industrial machines for lithography, and compact mobile SRF systems for security applications.

Thus, emerging SRF technologies suggest a bright future spanning the range from small compact SRF mobile industrial accelerators to very high power SRF-based industrial systems.

State-of-the-Art System Performance

Table 2-16 summarizes the present performance for SRF accelerators, taking typical performance from the Jefferson Lab CEBAF and Cornell ERL accelerators.

Table 2-16 Present SRF accelerator characteristics in context of E&E systems

	Present Performance	Note	Source
	Metric 1: Electron Beam Power		
Accelerator	17.8 MV/m	CEBAF upgrade (C100)	[1]
Window	13 kW	Waveguide coupler	[1]
	60 kW	Coaxial coupler	[2]
Electron Gun	75 mA	DC, photocathode	[2]
	Metric 2: Capital Costs		
RF Power System	$17/W	Small klystrons	[1]
	$13/W	Solid state	[2]
Accelerator Cavities	$60k/MV ($6M/100 MV)	8 x 1.5 GHz, 7-cell	[1]
Cryo System	$10k/W (~50M/5kW)	2.07 K He plant	[1]
Support Systems			
	Metric 3: Operating Costs		
RF Power	<50% efficiency		[1]
Cryo System	~1 kW/W	Wall plug/2K	[1]
Other			

[1] R. Rimmer, CEBAF parameters, private communication.
[2] R. Eichhorn, Cornell ERL parameters, private communication.

SRF System Technology Gaps

SRF accelerators have the potential for higher efficiency, even taking into account their cryogenic system needs. However, capital cost and reliability still need improvement to be competitive in the commercial arena. R&D is needed on new materials, less expensive accelerating structures, and compact, high-efficiency cryogenic systems. High critical temperature (T_c) material (such as Nb_3Sn, MgB_2, or other emerging materials) may make significant advances in overall efficiency. Alternative fabrication methods, such as thin-film coating on inexpensive substrates, may also result in cost savings and/or performance improvements. R&D in these areas may strongly impact overall system costs. SRF cavities have operated in storage rings with very high beam currents and high delivered power to the beam. Cavity designs optimized for low-energy, high-current electron linacs could be a topic for near-term R&D.

High-T_c SRF Systems

We noted above that the greatly increased heat lift of COTS cryocoolers operating around 8 K (6.7 times) using direct-conduction cooling of high-T_c SRF cavities enabled significant cooling cost savings, resulting in much lower CAPEX values competitive with DC systems for high-power E&E applications. The system would also be significantly more robust and, hence, suited for mobile applications. However, R&D for cavity fabrication using Nb_3Sn, NbTi-nitride, or similar materials that have T_c in excess of 16 K is required. The potential benefits here are substantial and also of considerable relevance to the basic DOE mission.

Improved SRF Cavity Heat Removal with Cryocoolers

The advantage of using high-T_c SRF cavities was identified above. There is also an additional need to develop, in parallel, the technology for effective direct-conduction cooling of the accelerating cavities, thereby eliminating the needs for cryogen baths. Development of this technology has the potential to both simplify and significantly reduce the cost of cryomodules for industrial and scientific accelerators.

2.10.4 New or Hybrid Accelerator System Approaches

The long-term goal of significantly reducing the capital cost of the accelerator per watt of beam power may require significant innovation and potentially new approaches to accelerator design. Emerging technologies, such as metamaterials and multiferroic materials, have the potential to reduce the size and potentially the cost of accelerator technologies. In particular, the use of metamaterials, multiferroics, or metamaterial structures for RF power sources is an active area of study [2-46], given the potential to reduce the cost and complexity by eliminating the traditional vacuum and cavity structures.

The unique properties of multiferroics and metamaterial structures could allow one to tailor the magnetic and electric field, as well as the material response, to electromagnetic waves simultaneously in a fully machinable bulk material. This capability is not possible in current RF designs and has the potential for substantial size and cost reduction.

Induction linear accelerators generate large peak currents at reduced duty factors. They utilize a large ferromagnetic core in the acceleration section that provides an acceleration pulse in the range of 30 ns to 1 μs.

Induction linacs utilize pulsed power as a driver. High current and short pulses are applied to the acceleration cells and the induced electric field in each cavity accelerates the electron beam. The acceleration cells use ferromagnetic material having a permeability of 100–10,000. The induction linac topology lends itself well to high current pulses. The pulse power of induction linacs can reach a few TWs. The acceleration gradient in induction accelerators is considerably lower than that of the RF accelerators, ~1 MeV/m. The typical efficiency of induction linacs is a few tens of percent. One such accelerator that could generate 70-ns pulses at 1.5 MeV was demonstrated and was designed to be portable or transportable [2-47].

2.11 Applicable Accelerator Technologies

The accelerators described in this report rely on several critical technologies. This section describes the state of the art and limitations of these technologies for reaching the target performance goals.

2.11.1 RF Power Sources

Technology Description and State of the Art

RF power sources can be used in multiple ways in accelerators. For example, they can drive beamline diagnostics, linearizers, or beam spreaders. For this document, RF power sources are mentioned in the context of a system which, in conjunction with an accelerator structure, accelerates electrons to high energy.

The RF system converts energy from the AC mains into a form usable within an RF accelerator system. Typically, this RF power is in the frequency spectrum from 0.1–20 GHz. In almost all cases, the AC power is initially converted into high voltage DC or pulsed power by an AC/DC power supply (or in the case of pulsed systems, a modulator). In turn, this high voltage power is fed to an RF source, which converts the input DC or pulsed power into a CW or pulsed high-power RF signal.

For the E&E applications discussed in this report, a primary requirement is high total average power (>500 kW). There is no preference for a CW or pulsed system, as long as the average power requirement is achieved. Requirements such as operating frequency, phase stability, bandwidth, and linearity are driven by the particular RF accelerator technology utilized in the system. Size, weight, and ambient operating conditions are not major constraints. The preferred technologies in the RF system are not specified, but the focus is on the overall system performance. Any DC power supplies, heater drivers, solenoid drivers, low-level RF systems, cooling fans, and phase-locking circuits are all included within the context of "RF system."

There are several requirements for RF systems in these applications. The desired metrics for the RF system are:

- Total RF system electrical efficiency >80% (AC-RF)
- Total RF system capital costs <$3/W (average power)
- Total RF average power >500 kW (with large scale systems >10 MW)
  - The power required from individual sources is determined by the accelerator technology that the power source is driving
- Robust, long-life system (greater than 50,000 hr)

High-power RF sources have been successfully utilized for RF accelerator applications for decades. A brief mention is included here of several technologies, which are active areas of study and are relevant in the regime of high average power and high efficiency. However, emerging technologies could also be applicable in this area.

Klystrons

Klystrons utilize a velocity-modulated electron beam in conjunction with one or more gain cavities and an output cavity to extract high-power RF from a bunched beam. Energy that is not extracted from the electron beam is deposited in a collector and is wasted.

There are many approaches to improve klystron efficiency. The "perveance" of the klystron—a measure of the space-charge effect in the klystron's electron beam—historically correlates with the tube efficiency. In general, high power tubes with high perveance are lower efficiency compared to lower power, lower perveance tubes [2-48]. For example, the 65 MW (peak), 2.0 μP SLAC 5045 is 45% efficient [2-49] while the 1 MW (average), 1.02 μP CPI (Communications and Power Industries) VKP-7952 is 64% efficient [2-50]. Klystrons are high gain (>40 dB) devices, so low-level RF system costs are a relatively small portion of the total system. In addition, focusing solenoids or large permanent magnets can be significant cost or power drivers.

Several development paths are being pursued on increasing the efficiency of klystron tubes. Multiple or sheet beams have been shown to increase device efficiency, while retaining a high effective perveance. For example, the 150 kW (average) multi-beam Toshiba E3736 has an efficiency of 66% with an effective perveance of 3.38 μP [2-51]. Recently, advanced tuning methods have been simulated to push the klystron into very high efficiency ranges (up to 90%) [2-52]. This technique is being applied to improve the SLAC 5045 klystron from 45% to above 65%, by changing the cavity tunings [2-53]. Finally, depressed collectors can be utilized to extract additional energy from the spent electron beam. The system efficiency can potentially be increased to over 80% with high power tubes [2-54].

Magnetrons

The klystron works as a high -gain linear amplifier driven by a low level signal. Its output phase and amplitude can be controlled at both low and high levels. In contrast, the magnetron is a saturated oscillator, which does not need a drive for oscillation at high power output, but can be seeded by a back injection signal through its output waveguide, in which case its output phase will follow the injection phase [2-55].

Operating as oscillators, magnetrons have an efficiency above 90% and are mass produced for several applications [2-56]. They are used in many lower average power commercial accelerators. For high power applications, R&D is needed to scale up to the >100 kW average power level [2-57, 2-58, 2-59].

The fundamental difference between a klystron and magnetron is the electron bunch formation: linear motion in the klystron and circular motion in the magnetron. Space charge effects in the motion dominate the efficiency. The spoke-on-hub bunches in a magnetron interact with the anode RF cavity in multi-gaps over multiple passes. Space charge de-bunching on the spokes is reduced. The beam bunching and power extraction in a klystron is a linear interaction with cavity gaps and involves only one pass [2-55].

There have been recent experiments with S-band magnetrons at the 1 kW level that were injection (frequency)-locked by a phase-modulated signal [2-56]. In addition, as a replacement for the CEBAF CW klystron system, a high-efficiency magnetron using injection phase lock and amplitude variation has been studied. Amplitude control was studied by using magnetic field trimming and anode voltage modulation [2-49].

Solid State Sources and Inductive Output Tubes

Solid state amplifiers (SSA) are a rapidly developing technology and have many positive characteristics. First of all, high power amplifiers are typically composed of arrays of smaller, modular units. The advantage of this approach is that redundancy can be built in and a single transistor or pallet failure will not prohibit continued operation. For example, operational experience at Soleil [2-60] has demonstrated over 40,000 hours of operation over 8 years with 100% operational availability. A second positive characteristic of SSAs is that there is a growing market and body of research on the devices. As they have uses both in high power and low power regimes, research in one application area (communications) will likely have relevance in other areas (such as accelerators). This is in contrast with vacuum electron devices which typically are focused on the high power regimes.

The primary disadvantage of SSAs is cost. Installed systems are typically greater than $12/W, even with RF transistors that are heavily commoditized. Presently, there is not a strong trend demonstrating that reaching the <$3/W system costs for E&E applications will be possible. Also, system efficiencies for SSAs are in the range of 50%. However, there is research into narrow-band SSA topologies such as class E and class F which may increase efficiencies of the amplifiers even higher. Nonetheless, until a system is demonstrated with significantly reduced cost, SSAs will have difficulty penetrating into the E&E accelerator market.

Inductive output tubes (IOTs) utilize a gridded gun to density modulate an injected electron beam. Resonant cavities are used to extract power from the beam. One advantage of IOTs is that they can operate with a high efficiency over a wide output power range. They are being actively considered for the baseline RF power source for the high-power proton accelerator of the European Spallation Source (ESS) [2-61]. Tubes with efficiencies up to 70% are commercially available [2-62]. However, the average power of individual IOTs has topped out at about 100 kW.

Technology Gaps

While several relevant RF sources have been highlighted in the previous section, the ideal technology for E&E applications does not favor any particular existing technology. In fact, future RF accelerators in this field may utilize sources that have, until this point, either not been fully realized or not been practical for more traditional accelerator applications. Also, any future RF system for E&E applications should be specified and developed in the context of the envisioned total RF accelerator system. In this way, cost and performance trade-offs for the RF system can be intelligently implemented.

While the heart of the RF system is the RF source itself, a holistic development of the RF *system* and, better still, the accelerator as a whole will likely yield the highest gains. Cooling systems, power supply systems, and RF drive systems can all be significant cost and efficiency drivers. Therefore, proportional emphasis needs to be placed in these areas.

Three key existing source technologies are highlighted in Table 2-17. Particularly in the area of cost, many of the demonstrated values are estimates; reliable data are not publicly available.

Table 2-17 Demonstrated performance of klystrons, magnetrons, and solid-state sources. Technology gaps are highlighted in ***bold****.*

	Demonstrated Values	Notes	Ref.
		Klystrons	
Tube Electrical Efficiency	64%	1.2 MW PEP-II klystron	2-63
AC-RF Electrical Efficiency	**60%**	Assuming 90% efficient power supply (neglecting low level RF and magnet power)	2-63
Tube Capital Costs	1. ~$0.60/W 2. ~$2/W	1. Approximate PEP-II 1.2 MW klystron procurement costs, escalated to 2015 dollars 2. Recent quotes for 500 kW systems	2-64
System Capital Costs	1. ~$0.90/W 2. $4–10/W	1. Approximate PEP-II klystron plus HVPS procurement costs, escalated to 2015 dollars (neglecting low level RF and other supporting systems) 2. Estimate for full installed system	2-64
Total RF Average Power	>1.2 MW	PEP-II klystron	2-63
Tube Lifetime	>50,000 hr	5045 klystrons	2-61
		Magnetrons	
Tube Electrical Efficiency	>90%	L3 magnetron oscillator	2-59
AC-RF Electrical Efficiency	**81%**	Oscillator, assuming 90% efficient power supply, not yet utilized in accelerator applications	2-59
Tube Capital Costs	n/a	Relevant tube not yet implemented	
System Capital Costs	$5–10/W	Estimate	
Total RF Power	**>100 kW**	L3 magnetron oscillator	2-59
Tube Lifetime	**1. ~8,000 hr** 2. 28,000 hr	1. Recommended replacement interval 2. 65 kW X-band magnetron	2-62, 2-65
		Solid State Sources	
Module Electrical Efficiency	68%		2-60
AC-RF Electrical Efficiency	58%		2-60
System Capital Costs	**$15/W**	Estimate	
Total RF Power	**180 kW**	SOLEIL SR	2-60
Lifetime	>50,000 hr		2-60

Technology gaps for klystrons:

- Demonstrated high system efficiency at relevant average powers
  - With a presently demonstrated AC-RF system efficiency of ~60%, klystrons do not meet the >80% efficiency requirements for E&E applications.

Technology gaps for magnetrons:

- Demonstrated high system efficiency (with phase locking and sufficient phase stability) at relevant average powers
  - Phase-locked magnetrons have not yet been demonstrated in high average power RF accelerator applications.
  - The high efficiency as an oscillator (>80%) has not yet translated into an amplifier powering a high average power accelerator.
- Demonstrated long-life operation at relevant average powers
  - High power magnetrons have not demonstrated the long lifetimes required for E&E applications.

Technology gaps for solid state sources:

- Demonstrated high system efficiency at relevant average powers.
- Need for order of magnitude reduction in system capital costs.

2.11.2 Power Couplers

Technology Description and State of the Art

Many existing RF vacuum tubes have output windows that operate at megawatt power levels, and these or similar designs are often adapted for accelerator use. For reliability, it is advisable to de-rate these in the accelerator application compared to tube use because the environment in the accelerator is not as well controlled as in the tube. Both coaxial and waveguide type windows have operated at megawatt power levels on tubes and in test stands and have delivered ~0.5 MW to beams in accelerators. These are adequate for near-term use and pilot-plant applications but may become a limitation at the time of scaleup to very high power systems. They can also be expensive and sometimes use undesirable materials, such as beryllium oxide, to achieve the highest power throughput. R&D to develop simpler, more reliable, and less expensive couplers in the megawatt class would be desirable. Alternative (but not necessarily new) materials and construction techniques could be evaluated. Redundant (double) window configurations may be desirable for reliability. Improved interlocks and diagnostics may be desirable. For systems requiring variable beam power, adjustable couplers may be desirable to maintain optimum efficiency; however, these typically introduce complexity and cost. Novel schemes for adjustability of high power couplers that avoid these complications may be desirable.

Technology Gaps

- Low cost, high reliability MW class windows and couplers (excluding toxic or exotic materials, e.g., beryllia), in the 0.3 to 1 GHz range
- Alternative window materials with lower RF losses and/or better thermal and mechanical properties than traditional alumina and availability from multiple commercial vendors to ensure reliability of supply.
- Simple redundant (e.g., double) window configurations in which the outer window may be replaced in situ without compromising the inner window and cryomodule vacuum.
- Simple and reliable adjustable couplers to allow for optimum matching under day to day variations in beam loading.
- High reliability instrumentation for coupler vacuum, temperature monitoring, electronic activity etc.
- Advanced coating or processing techniques to reduce conditioning time and/or improve long term reliability of windows.

2.11.3 High Current Electron Sources

Technology Description and State of the Art

High-current electron sources are needed for megawatt-scale DC accelerators and RF accelerators. The sources must satisfy multiple criteria to meet the high average current and brightness needed for E&E applications. Building an ampere-class accelerator for E&E applications differs significantly from accelerators normally used in the DOE Office of Science programs. Requirements on the beam quality may be lower, whereas requirements on robustness, reliability, and ease-of-operation are critical, all while keeping the electron gun cost low. On the other hand, the beam quality requirements may, in fact, still be important since the beam halo must be kept low at very high currents.

Present Technology. As demonstrated by existing high-power DC systems and RF systems, present guns can produce high CW currents on the order of 100 mA. Present industrial DC accelerator cathodes have been utilized up to the 160 mA level and accelerated to >1 MeV as needed for E&E applications. These cathodes operate for 15–20,000 hr with the existing electron-gun technology at the 160 mA level. In the RF accelerator, the peak current generated at the cathode is near the 1-A level, and average currents delivered are 100 mA.

Future technology: E&E applications will require electron sources with ampere-level current. This means that better beam control (i.e., less beam loss) will be required as the average current and power is increased to mitigate activation of the accelerator. The existing cathodes may perform at considerably higher currents, but this needs to be demonstrated. For example, gridded guns used for IOTs are capable of up to 5-A CW operation; however, this beam needs to be integrated into the accelerator and transported with low beam loss to the end of the accelerator at high energy, 1–10 MeV. Another proven solution is the gridded RF gun placed external to the acceleration cavity where, to obtain the short bunches required, the RF gun operates at a frequency harmonic of the linac. In general, the cathode current density typically should not exceed 2 A/cm^2 to provide good longevity.

Future technologies to enable high-power E&E electron sources are as follows:

- Material. Different cathode materials and sizes should be considered, and a selection should be made to allow un-interrupted operation for at least 8000 hr at high average current.
- Beam Dynamics. The electron source should provide short bunches with low longitudinal and transverse emittance in order to minimize the beam current interception in the accelerator and beam delivery system. In addition, for the RF accelerator, the electron source should produce short bunches. The beam current intercepting the accelerator walls should not increase the total power losses significantly; thus, it should not exceed the level of few tens of kilowatts, or about 1–2% for the NCRF accelerator and much less for the SRF accelerator. Thus, space charge effects should be investigated and focusing schemes developed to allow for a compact layout with low beam interception. The cathode should provide a pulse current of 1–2 A for a 10 MeV linac in CW regime, and even more for pulsed operation with a small duty factor.
- DC Power Supply. The solid-state rectifiers used in DC accelerators are currently limited to a maximum current of approximately 100 mA per rectifier. Development of new solid-state rectifiers that could handle 300–500 mA beam current is one path forward.
- RF Power Supplies. Present RF accelerator produces 0.7 MW of beam power from 1.4 MW of RF power for an RF-to-beam efficiency of 55%. To increase the beam current to ampere class, the RF power coupled into the cavity must also increase.

Technology Gaps

High average current (ampere-class) electron sources are needed for both DC and RF accelerators used for E&E applications. This represents about an order of magnitude improvement beyond today's state-of-the-art source. The future electron source must demonstrate high average current beams coupled into an accelerator system (DC, NCRF, and SRF accelerator) with appropriate halo control and transport through the accelerator system (i.e., accelerator column or RF accelerator structure) while maintaining long lifetime (>8000 hours at high average current).

Start-to-end simulations from the cathode to the exit of the accelerator are needed to demonstrate low beam interception and proper space charge handling. The beam current intercepting should not increase significantly the total losses determined by the ohmic losses. The DC accelerator electron sources, in particular, would benefit from the development of solid-state rectifiers that could handle in the range of 300–500 mA per rectifier. The RF accelerators need increased RF power coupled into the accelerator to allow for high beam power.

2.11.4 Secondary Accelerator Technology Needs

Windows

High-power scanner windows exist today; however, megawatt-class systems, improved interaction zone geometries, and higher power density applications may increase the power density that needs to be handled.

Beam Stability
At ampere beam currents and low energies, beam stability and losses may be of concern. Beam break-up due to higher order modes (HOMs) in the accelerator may need to be mitigated by damping of the HOMS. This is a well understood issue that needs careful evaluation on a case-by-case basis. However, high bunched beam currents may induce significant power in the HOMs that needs to be safely extracted. This extraction may be more difficult for superconducting accelerators than normal-conducting ones due to the sensitivity to any additional heat load into the cryogenics. Suitable microwave-absorbing materials are available that are compatible with accelerator applications. Specific accelerator designs will need optimized HOM dampers to be designed and developed.

Beam loss and stray particles (halo) may be a concern at high powers, especially for superconducting accelerators. Modeling will be important in the design of the electron sources and transport into and through the accelerator. Collimation may be of some help, but minimization of halo during the bunch formation will be more beneficial.

Accelerator Cost Reduction
Compared to existing technologies, accelerators may still have an unfavorable capital cost in some cases. In addition to the efficiency improvements and component cost improvements above, R&D on the basic accelerator structures themselves may be beneficial in terms of capital cost reduction and overall system simplification. Despite the fact that accelerators have been built for many decades, "design for manufacture" and economies of scale may still yield benefits.

Design for availability
Accelerators that are designed to support basic scientific research are not typically designed to meet industrial-class system availability specifications (>95%). High availability can be achieved, but it requires a serious design consideration from the beginning of the system design process. Achieving high availability is an overarching requirement for any industrial application of new accelerator technology.

2.12 Near- and Long-Term R&D Impact

This section describes R&D thrusts that have the potential to impact the field of accelerator applications in energy and environment. The R&D thrusts are divided into near-term (1–5 years) and long-term (5–10 years) and categorized as either high impact or medium impact. Low impact R&D areas are not considered.

Figure 2-8 shows the identified R&D thrusts and the impact that progress in those thrusts would make on reaching the accelerator capability and performance targets outlined in this chapter.

R&D Thrusts	Demo/pilot scale (0.5 MW, 0.5-1.5 MeV)	MW-class DC system (1 MW, 1-2 MeV)	MW-class high-energy (1 MW, 10 MeV)	Ten MW-class high-energy (10 MW, 10 MeV)
	Target Accelerator Capabilities			
DC Systems: HV, high current	1	1	3	3
NCRF Linac Systems: structures, performance	3	3	1	2
SRF Linac Systems: structures, performance	2	3	1	1
Beam Dynamics	2	1	1	1
Electron Sources	2	1	1	1
RF Power Systems: higher efficiency, lower cost	3	3	1	1
SRF materials and cavity fabrication	3	3	1	1
RF delivery components	3	3	1	1
Beam windows	3	2	2	1
Portability, field-ability	2	2	2	2
System-level demonstration	2	1	1	1
Commercialization viability	2	1	1	1

1	Very important
2	Somewhat important
3	Not important or not applicable

Figure 2-8 R&D thrusts and the impact that progress in those thrusts would make on reaching accelerator capability and performance targets.

2.12.1 Near-Term R&D Thrusts

High Impact

- DC accelerator systems:
  - Improve reliability aspects of high voltage and power conversion systems; improve reliability with respect to high-voltage breakdown, insulators, capacitors, and other HV system components.
- NCRF-based linacs:
  - Optimize RF cavity designs for low-energy, high-current electron linacs targeting 90% efficiency (RF to beam).
- SRF-based linacs:
  - Reduce cryogenic losses through high-quality factor SRF structures.
  - Optimize SRF structures for high-current, low-energy applications (a very different optimization from that of DOE High Energy Physics programs).

- Beam dynamics:
  - Deploy modern beam dynamics codes in new contexts relevant for low-energy, very high-current applications. Simulate beam loss and stray halo particle loss. An example would include the design and shielding of accelerating columns for ampere-class beams.
- Electron sources:
  - Develop and demonstrate (including characterization of beam halo) ampere (and multi-ampere?) class sources with appropriate beam quality for injection into an accelerator (either DC or RF linac, most severe for SRF). High-current (5 A) sources exist but at 10s of kilovolts. There is a gap in taking this high current to high enough energy to couple into an accelerator system.

Medium Impact

- Supporting technology and components:
  - Develop simpler, more reliable, more efficient, and less expensive RF delivery systems, including couplers, windows, circulators, and waveguides in the megawatt class.
  - Improve beam power handling of window systems and develop windowless approaches.

2.12.2 Long-Term R&D Thrusts

High Impact

- DC accelerator systems:
  - Develop approaches for handling very high DC beam currents in accelerating columns.
- SRF-based linacs:
  - Conduct R&D for SRF cavity fabrication using Nb_3Sn, NbTi-nitride, or similar materials that have T_c in excess of 16 K.
  - Develop technology for effective direct-conduction cooling utilizing cryocoolers.
  - Develop alternative fabrication methods, such as thin-film coating on inexpensive substrates, that may result in cost savings and/or performance improvements.
  - Develop cold-cathode SRF gun technology.
- RF power systems:
  - Total system: Any technology utilized must be high efficiency, low capital cost, and designed to operate into a relevant accelerator system. <u>System</u> efficiency greater than 80% is desirable with capital cost less than $3/W.
  - Klystrons: Demonstrate high RF system efficiency at relevant average powers.
    - With a presently demonstrated AC-RF system efficiency of ~60%, klystrons do not meet the >80% efficiency requirements for E&E applications.
  - Magnetron: Demonstrate high system efficiency (with phase locking and sufficient phase stability) at relevant average powers.
    - Phase-locked magnetrons have not yet been demonstrated in high average power RF accelerator applications
    - The high efficiency as an oscillator (>80%) has not yet translated into an amplifier powering a high average power accelerator.

    - Magnetron: Demonstrate long-life operation at relevant average powers.
        - High power magnetrons have not demonstrated the long lifetimes required for E&E applications.
    - Solid-state RF:
        - Demonstrate high system efficiency at relevant average powers.
        - Attain order of magnitude reduction in system capital costs.
- Electron sources:
    - Demonstrate high-current source coupled to an accelerator system (NCRF linac, SRF linac) with appropriate halo control and transport in the accelerator system (accelerating column or linac structure).
- Portable high power systems:
    - Demonstrate system-level engineering for portability, transportability, field-ability, and turn-key operation.
- System level:
    - Demonstrate multi-megawatt high-energy systems with target electrical efficiency and availability/reliability.
    - Demonstration of NCRF-based system capable of >50% AC-beam efficiency, including RF and all support systems in the 10 MeV, 1 MW and higher-class systems.
    - Demonstration of SRF-based system capable of >50% AC-beam efficiency, including RF and cryogenic cooling in the 10 MeV, 1 MW, and higher-class systems.
- Commercialization:
    - Demonstrate capital cost goals (<$5–10/W depending on system).
    - Demonstrate wall-plug to beam-power efficiency goals (>50–75%).

Medium Impact

- Develop solutions for SF_6-free operation.

3. Applications of Superconducting Systems

Superconducting materials and magnets are a key enabling technology for accelerators. Two applications in the E&E area that could benefit from ongoing HEP R&D are wind generators and magnets used in waste separation.

3.1 Wind Generators

3.1.1 Background and State of Application Development (Q1)

With a few exceptions (e.g., the 7.5-MW wind turbine with 126-m rotor diameter manufactured by Enercon [3-1]), current technology limits the generation capacity of land-based wind turbines to around 3 MW, mostly due to transportation of blades and tower sections over highways. Offshore systems are presently approaching 8 MW, with limitations mostly due to crane capacity with regard to mass and height. As a frame of reference, some papers have estimated that a 10 MW, non-superconducting direct drive generator might weigh 350 tons, while various paper design studies using superconductors have estimated superconducting 10 MW generators in the range of 50–200 metric tons, depending on machine design, superconductor, and cryogenic temperature. Availability and logistics of larger crane classes make scaling up to higher capacity challenging. The current trend is toward increased rotor diameter (and thus lower specific power, W/m^2) and higher hub heights.

Continued development is needed to reduce the size, mass, and cost and to increase the reliability and efficiency of wind turbine drive trains [3-2]. Permanent magnet (PM) and superconducting direct drive (DD, i.e., no gearbox) generators are competing technologies. Each offers advantages of higher capacity factors for low wind speeds relative to wound-field drivetrains. The benefits of superconducting wind generators come mostly from their size and weight reduction, which reduces tower, foundation, mounting, and transportation costs. There may be some improvement in efficiency, but that is usually on the order of a few percent. National Renewable Energy Laboratory (NREL) analyses of superconducting turbines [3-3, 3-4] showed that they were favored at large capacities over PM-DD designs, where cryogenics, torque, and flux density were identified as important factors. The present development of PM-DD systems for the 4 to 8 MW range pushes most superconducting suggestions to large sizes, ~10 MW or higher, for offshore farms. There is a general economic problem for offshore wind in that both up-front capital costs and the levelized cost of energy (LCOE)[2] are presently about three times higher than the equivalent costs for onshore wind. However, offshore wind presents interesting opportunities to attain a higher capacity factor, location near population centers, and overlapping of peak wind periods with highest electrical demand [3-5], as discussed in more detail later. Strategies [3-5, 3-6] have identified several opportunities for reducing the cost, along a roadmap that predicts comparable energy costs for 8 MW systems by 2020 and lower costs of energy for 10 MW tower ratings by 2030. The size/weight advantage of superconducting machines is greatest for large DD generators, but that must be traded off economically against smaller conventional high-frequency generators connected to improved gearing, as well as the requirements for full power conversion for low-frequency DD machines. Intermediate frequency generators may be coupled with a single-stage gearbox for conventional, PM, or superconducting

[2] The levelized cost of energy is the annualized capital equipment cost, fees, operational costs, and maintenance costs divided by the annual energy production (AEP), taken over the expected lifetime of the farm.

versions. A general uncertainty is whether gearboxes of any kind can be highly reliable at the huge torque ratings for 10 MW turbines, especially in view of the difficulty of offshore maintenance.

The LCOE includes wind availability, which improves with tower height. This is the primary metric that drives wind farm economics. Several factors favor increase of tower height:

1. Taller towers with longer blades and higher torque ratings benefit from a faster wind field on average. Shear effects for offshore wind are, furthermore, smaller than those on land, which improves the quality of the vertical distribution of wind velocity. While wind farm power density (MW/km^2 land or water area) improves with tower height, this is only because of the higher average wind velocity across the farm; fans "deflect" the wind stream, and a lateral separation proportional to the tower height is required to allow the wind field to return to the fan area. This negates the gain in power produced per tower.
2. Large fans have a lower specific power (W/m^2 of fan area), which improves the power curve as a function of wind velocity, i.e., slower winds produce enough torque to maximize the output of the generator.
3. With fewer larger machines, the connection costs per megawatt should be lower; some estimates suggest as much as 30% less connection costs by scaling to 10 MW fans.

Wind generator technology is making continuous progress. Current technology is capable of building generators up to 8 MW. Large-scale deployment of 6 MW PM-DD turbines has been initiated for off-shore wind farms in France. These improvements are a consequence of industry investment in R&D that is orders of magnitude greater than government R&D. Risk avoidance and other factors favor industrial R&D that is incremental upon established technology, which has slowly evolved from conventional copper and iron generators with multi-stage gearboxes to parallel development of PM generators without gearboxes, and generators with single-stage gear boxes. The R&D is also confronted with the complexity of a turbine, where advances in power electronics have been required to facilitate development of DD generators turning at low frequency. Industrial R&D has thus been broadly based, with advances in generator and drivetrain technology being only part of the overall portfolio.

Thus, the present state of wind turbine technology is difficult to assess due to the competition between different platforms and the complexity with which the LCOE is calculated. No single parameter or index characterizes a preference (e.g. for geared systems, over PM-DD systems or superconducting systems). The LCOE is the only means to determine the winning strategy, since it is the primary index that contributes to the operating margin. It is clear that superconducting generators have very high specific power (kilowatts per kilogram), and that reduction of the weight on top of the tower is a significant factor in reducing both the cost of the tower and the cost of construction. Nonetheless, the overall benefit to LCOE is not easy to determine. The parameter space is large and interconnected, meaning that small engineering changes to the design of, say, blades has consequences for the drivetrain, control electronics, operating conditions, and other factors that feed into a lower LCOE for an alternative design. Moreover, farm-level integration provides a second level of optimization, which may reduce or remove completely any preference for one parameter choice over another. When two approaches offer the same LCOE, a manufacturer is likely to choose the one with lowest non-recurring engineering or lowest risk factor, i.e., the one which costs less to commercialize. This leads to the conclusion that cost comparisons need to be done on a system (total wind farm output) basis.

The present wide range of possible scenarios for the 4–10 MW range creates a rich spectrum of competition. It is clear that increased tower height and increased fan area (Fig. 3-1) offer advantages that could lead to lower LCOE. This drives technology toward larger fans and increased torque. Offshore wind provides additional advantages of a more reliable wind source, location near population centers, less boundary-layer shear, high wind velocities during peak periods of electrical use, and freedom from land-based constraints such as overpasses and other transportation obstacles. However, offshore wind is confronted by a number of challenges, such as foundations and tower requirements, harsh operating environments, remote locations, difficulty of construction and service, and need for interconnections. The complexity of systems means that adaptation of a winning land-based configuration to offshore installation might not result in a winning LCOE, so it is important for manufacturers to maintain a variety of design options.

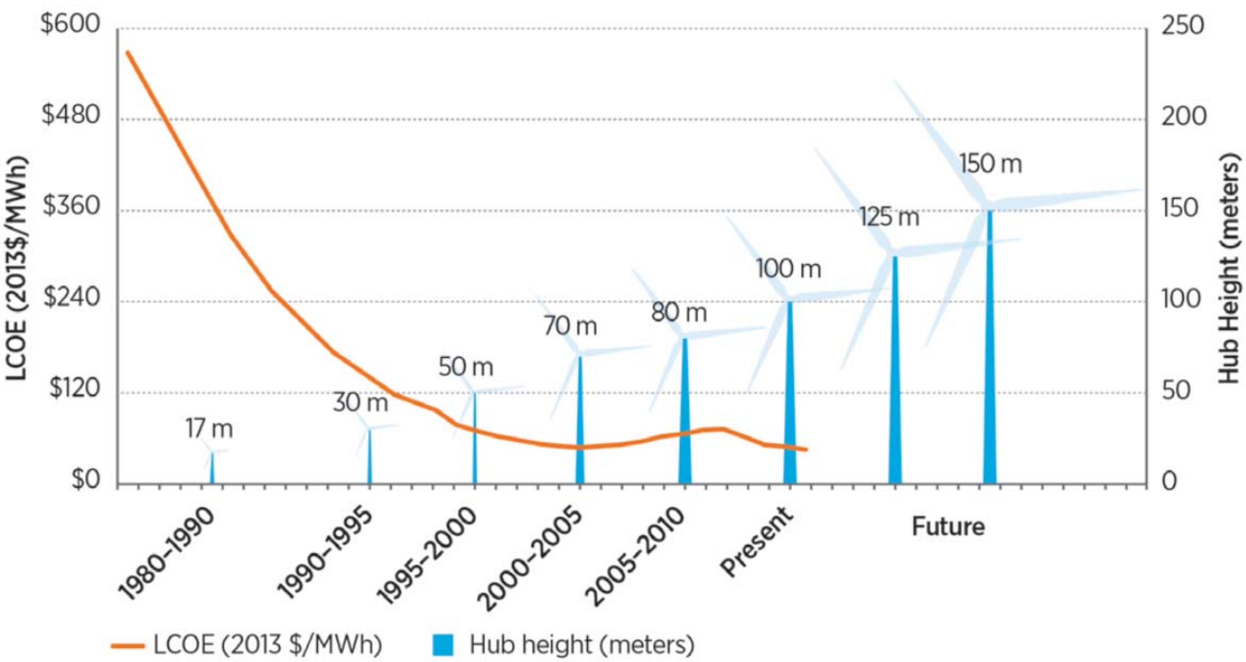

Figure 3-1 Wind technology scale up trends and LCOE [3-7].

Furthermore, wind farms are tailored to the details of specific locations. Flexible turbine designs fuel the ability of manufacturers to design wind farms for different constraints, including adjustments to particular terrain associated with a potential wind farm, the anticipated wind availability for the location, load patterns, and other factors. It is not known whether offshore opportunities reduce the breadth of design space by removing geographic details. Furthermore, the projected economic opportunity for wind generation systems means that certain technological advantages, such as advances in bearings and gearboxes, might be closely guarded. The true state of the technology must, then, be assessed by synthesis of data from many sources, especially those based on the published literature, and those based on reasonable extensions of technology privately held by the major turbine manufacturers.

The major potential contributions of accelerator technology to offshore and onshore wind technology are in the construction of drivetrains. Two main classes of drivetrains were envisioned by the BRN panel: (1) superconducting field coils on the rotor with copper coils on the stator that could be constructed as iron-core or air-core and (2) superconducting coils used for both field coils and armature coils. Since no superconducting machine has been deployed to the field, only design studies are available for comparison.

3.1.2 Regulatory Framework (Q2)

The use of superconducting technology should not result in additional regulatory issues beyond standard engineering requirements related to pressure vessel codes, welding codes, and hazardous material identifications (if any).

The LCOE is strongly affected by political initiatives and regulations governing the operation of the grid. In addition to customer-based feedback about the choice of electric power generation, treaty mandates, adoption of carbon taxes, feed-in tariffs, subsidies, and other regulatory actions associated with climate change could have significant effects on the LCOE. The Federal Energy Regulatory Commission (FERC) and State regulators may impose additional restrictions on the quality of power being delivered to the grid. Some of these restrictions are reactive power (VAR) capability and control and low-voltage ride through, which keeps a wind farm from dropping off the grid and exacerbating the grid problem when some event causes grid voltage to drop. It was noted that superconducting systems may offer a unique solution relative to PM machines due to controllable field excitation. This greater control may enable a wind farm to meet some desired or regulated output control parameter more easily. All of these parameters contribute to the vast array of turbine design options.

3.1.3 Economic Analysis (Q3)

The complex interaction among the several parameters defining the LCOE makes it difficult to single out certain parameters that define opportunities for superconducting systems, permanent magnet systems, or conventional systems with gearboxes. All of these technologies are being developed in parallel, so this comparison will not be stationary in time.

Superconducting systems are believed to offer opportunities in lower mass per unit power delivered. This capability could be useful, or even enabling, for construction of large towers with high power capacity. Superconducting turbines are thought to enable several options beyond 10 MW. The following criteria were determined by the workshop panel to be important for the further development of superconducting turbines:

- Reliability of coil and cryogenics: Operation of the superconducting unit and its associated cryogenics must not affect the operation of the wind turbine. Remote operation with long periods between maintenance cycles must be tolerated. Demonstration of highly reliable coil systems and cryogenics would remove risk for deployment, which is essential to encourage adoption of the technology. Examples are advances in basic understanding of margins and fault conditions associated with coils, which would lead to manufacturing techniques that integrate quench management and prevention strategies into coils design. Higher annual uptime directly increases the AEP, which reduces the LCOE.

- Thermal margin: No failures of any kind may be permitted in the superconducting windings. Disturbances, both internal and external, should not result in quenching of the magnets or failure of the superconducting component. Recovery from an episode should not result in a significant risk to operations. Assurance of operation without fault conditions and protection against unlikely external events reduce the LCOE by increasing the operational lifetime.
- Identification of fault conditions and protection: The operating environment of a wind turbine generator is noisy, which creates several challenges for identifying signals that indicate potential loss of superconductivity, which could result in the failure of a coil. Quench detection schemes, protection countermeasures, and other means to ensure the prevention of any loss remove risks for operation. Understanding of faults could result in operational envelopes that maximize performance and remove unnecessary safety margins, thereby reducing LCOE.
- Reduction of conductor and coil cost: While the cost of the superconductor is a contributor to the cost of the coils used in a wind turbine generator, there is usually a trade-off between the amount of superconductor used and the weight of the generator. Lower weight requires more compact coils, higher fields, higher ampere-turns, and higher current density. These conditions place a premium on the superconductor used. The development of less expensive superconductors at equivalent performance directly results in lower superconducting generator cost.
- Understanding of cryogenic systems in the 10 W to 1 kW cooling range: On the technology side this understanding is essential for the demonstration of reliability. Calculations of LCOE values can vary significantly due to uncertainties in the cost and operation of the cryogenic systems. Often, uncertainties of 50% or more are generated by lack of information. Improved information here could contribute to refined calculations and more accurate LCOE values. This information is needed for service over a wide range of cryogenic temperatures. Depending on the superconductor used, the desired cryogenic temperature range is 4–77 K.

3.1.4 Performance Criteria (Q3)

Weight reduction is the key advantage of superconducting wind generators. There may be some improvement in efficiency, but that is usually minor [3-4], and superconducting systems must still expend energy to maintain cryogenics when the wind speed is below the cut-in threshold. An all-superconducting drivetrain target should be less than 300 tons mass for 10 MW rating. Power per unit mass (MW/ton), torque per unit mass (N-m/ton), and cost per power ($/MW) are important. Offshore comparisons in [3-5] target <$3,000/kW nameplate capacity capital cost to compete with onshore turbines. Targets for LCOE in national program goals are between 3 and 5 cents per kW-hr [3-2, 3-5].

Economics are dependent on per-tower crane cost, so even though superconducting options are expensive, construction of 10 MW high-power PM-DD machines may be even more so.
Cost of superconductors contributes approximately 30% or more to the cost of field coils. Coil R&D activities are difficult to sustain for conductors above about $5/kA-m, and competitive

technology may require costs at around the \$1/kA-m level. Except for Nb–Ti, superconductors in the HEP portfolio are used at or above the \$5/kA-m target, with the primary intention of reaching very high magnetic fields. Scaling laws can be applied to map conductor costs from fields and temperatures in which performance data are available for the potential field and temperature ranges where drivetrains might be considered. Here, cost reduction by a given factor can only be met if a sufficiently steep slope of performance improvement with reduced field and/or temperature is available, since the cost per meter is generally fixed by the production method. For example, Nb_3Sn and possibly MgB_2 conductors above 5–8 K and 1–5 T may fall into the cost targets. For other, higher T_c materials, factors of 20–100 improvement by a sufficient number of kiloamperes is not possible within the available space for field and temperature reduction, so reduction of the basic conductor cost per meter must be attained.

3.1.5 Technical Gaps (Q4)

The challenges of superconducting wind turbines can be related to gaps in six basic research areas:

1. Whereas HEP magnets are designed for, and operated in, liquid helium, optimizations for wind turbines can favor temperatures well above 4.2 K. Experience with coil technology above ~5 K, such as under conduction-cooling conditions, is lacking, especially at the 1–5 T field ranges indicated for 10 MW turbines. Accelerator technology is only mature technology for Nb-Ti magnets (T_c = 4.2 K), yet the most advantageous use of superconductors for turbine drivetrains could be at higher temperature with other materials.
2. Some candidate superconducting wires for 5–75 K and 1–5 T are expensive, well above the target \$5/kA-m. A restricted opportunity space for Nb_3Sn and MgB_2 might be identified, but the field and temperature may also result in marginal stability. The lack of availability of a low-cost superconductor hinders the development of coils and acquisition of operational experience for wind generator components.
3. Besides cost, conductor performance must meet requirements for current, strength, ease of manufacturing, length, architecture, stability, dimensional tolerance, and other factors. Performance data are generally not available at the field and temperature range envisioned for wind generators, making conductor specification difficult. Test facilities generally do not probe kiloampere currents, other electromagnetic properties, thermal properties, and mechanical properties across the 5–60 K range, making verification difficult as well. These performance aspects also hinder the adaptation of superconducting technology for wind turbine generators.
4. Reliable quench protection of high temperature superconductors (e.g., YBCO and MgB_2) has not been proven in coils above ~20 K. Slow development and propagation of normal zones also concentrate thermal gradients, which result in high local stresses during quenching. Detection of quenches, protection of magnets, and managing stresses during quenching are unsolved problems of concern.
5. Efficient cryocooling systems with minimal maintenance requirements are not yet demonstrated at the required scale. The cryocooling industry is rapidly improving at present; however, magnet technology still lags in experience.

6. Superconducting stators (armatures) and AC losses in the conductor drive systems toward low frequency. This effect, in turn, increases the size and cost of the frequency conversion electronics. Hence, R&D addressing both of these issues is required.

3.1.6 Synergistic Application-Side R&D (Q5)

Synergistic applications for wind turbine applications extend from the similarity between drivetrains and other rotating electrical equipment. High torque density is an envisioned advantage of superconducting motors for aircraft propulsion. Although the frequency of operation for electric aircraft motors would be much higher than that for wind turbines, the basic technologies for coils and cryogenics share significant overlap. It is possible that aircraft propulsion units can be adapted to wind energy drivetrains.

Ship propulsion motors are also very similar to wind turbine drivetrains. Here, the rotational frequency and power ratings are very similar. Advances in coil technology, cryogenics, seals, shafts, bearings, and other components from superconducting ship propulsion applications should be directly relevant to wind turbines. Hydrogenerators are another example of low-speed, high-torque rotating machines.

Development of superconducting magnet technology addresses the same fundamental themes underlying rotating machinery: development of coil fabrication techniques, increase of superconductor conductor performance, reduction of cost, and improvement in cryogenics. There is also a need to address interfaces by developing advanced composites that manage thermal conduction and studying ancillary materials such as insulation.

3.1.7 Required R&D to Bridge Technical Gaps (Q6)

1. **Build, test, and operate superconducting coils in the temperature range between the boiling points of liquid helium and liquid nitrogen.**
   - *Summary*: The tradeoff between higher complexity of cryogenics and better performance and wider selection of superconductors may be optimized for temperatures between 10 and 35 K for wind turbines. Research programs in this area would directly address the lack of experience in magnet technology under these conditions, since most magnets are operated with liquid cryogens below 5 K or at 65–77 K. The outcomes of programs would greatly reduce the present uncertainties for cost and reliability of coils, drivetrains, cryogenic systems, AC losses, and frequency conversion electronics, which are the primary uncertainties transferred to the LCOE for superconducting drivetrains.
   - *Research Directions:*
     - *Targeted conduction-cooled coil development*: Development of small-scale, 2–6 T coils should be possible for Nb_3Sn conductors at 8–12 K, MgB_2 conductors at 8–25 K, Bi-2212 ($Bi_2Sr_2CaCu_2O_x$) round-wire conductors at 8–20 K, Bi-2223 ($Bi_2Sr_2Ca_2Cu_3O_x$) tape conductors at 8–25 K, and ReBCO ($ReBa_2Cu_3O_{7-x}$, Re= rare earth) conductors at 8–60 K. These temperatures are generally reached by conduction cooling to modular cryocoolers. Testing and operations will provide knowledge about the effectiveness of present coil manufacturing technology under these operating conditions.

- *Alternative cryogenic systems*: Development of efficient cooling systems based on circulation of high-pressure cold helium through coil structures with embedded tubing. Develop efficient cooling systems with 2-phase or single phase liquid hydrogen, neon or nitrogen, or mixtures.
- *Basic conductor information*: Additional information about the properties of superconducting magnet conductors at temperatures other than 4.2 or 77 K. This information is generally inadequate for magnet development. Scaling relationships exist to provide extrapolations, but some have been shown to be unreliable. Feedback about magnet-relevant issues to conductor manufacture could be improved. Test facilities to measure current density, current-voltage scaling (so-called "n-value"), current transfer and magneto-resistance, magnetization, and other electromagnetic properties from 8 to 60 K would be very useful. For flat conductors, measurement of properties as function of field angle to the surface is important. For superconducting armatures, development of fine filament conductor to minimize AC losses is needed.

- *Challenges*: National laboratories that develop magnet technology for particle accelerators, large physics experiments, and basic science have established infrastructure for the 1.8 to 5 K temperature range of operation. Installation of, and experience with, conduction cooling will require modification of facilities and related cryogenic engineering for support structure, such as current leads. While, in principle, the infrastructure used to fabricate coils for operation at 4.2 K can also be used for coils operating at other temperatures, research activities could instigate changes in instrumentation, power supplies, materials, and tooling. Laboratory and university facilities have many capabilities for variable-temperature property measurements, except perhaps the ability to measure transport current of kiloampere-class magnet conductors at 8 to 60 K. Coordination of property information between characterization labs is a significant need.
- *Potential impact*: Targeted development and operation of many small coils, especially in the 2–6 T and 10–35 K range, would provide key information to remove operation and reliability uncertainties. This information should remove the most significant uncertainties against application of superconducting magnets in wind turbines, as well as provide greater market acceptance of superconducting magnet technology as a whole. The modularization of magnet systems via conduction cooling offers an interesting alternative for large physics projects by disconnecting large central helium liquefaction. However, loss of the liquid cryogen cooling pool makes ride-through of cooling problems more difficult. Since all magnets experience temperature rise during quench, protection and instrumentation strategies developed here could greatly advance the application of magnets at liquid helium temperature and very high field.

2. **Develop a basic understanding of stability, quench, and other origins of magnet failure when operated at elevated temperature.**
   - *Summary*: Reliability requirements of wind turbines necessitate that field coils should never experience a failure of any kind. Yet, the understanding of magnet stability and quench for operating points above 10 K is not sufficient to meet this requirement at present. The increase of heat capacity with temperature reduces the rate at which quenches propagate, compared to niobium-based magnets at 4.2 K, making magnets

prone to hot spots and burn-out. On the other hand, the possibility of a large thermal margin between the critical temperature and the operating point means that small disturbances, such as coil motion, cannot initiate a quench. These conditions have significant implications for magnet construction, instability detection, quench countermeasures, instrumentation, and other components essential to magnet technology. Basic understanding could lead to a more consistent strategy for ensuring quench-free operation of magnets above 10 K. Moreover, advanced understanding here could result in construction paradigms that span the range of available conductors, providing the flexibility desired by the complex wind turbine market.

- *Research directions*: In conjunction with coil development programs, study of quench and stability should be broadly based on fundamental parameters and computational modeling. Quench protection, quench detection, and thermal margins are subjects where basic information is lacking from basic conductors and turn-to-turn connections, as well as across full layers of coils. The advantages and drawbacks of pancake vs. layer winding for stability should be understood. Quench detection should anticipate noisy electromagnetic environments of wind turbines. Thermal expansion, strain, and strain-dependent properties are contributors to instabilities and quench initiation. Ultimate limits of conductors, such as temperatures at which permanent degradation occurs, are only known for some materials.
- *Challenges*: The lack of thermal propagation can produce a situation where voltage detection across coil terminals by a computer reading an instrument may not be quick enough to prevent damage. Custom electronics, new detection techniques, and turn-by-turn local sensors might be required to distinguish instabilities, especially in noisy environments. Basic models of quench behavior are confronted by challenges from material interfaces, poorly conducting and insulating materials, lack of material data for emerging conductors, and new magnet designs (existing models cannot be ported simply).
- *Potential impact*: Quench protection underlies broadly the implementation of new high-field magnet technologies using superconducting materials that are not based on niobium. Better understanding of quench and stability for coil operating conditions relevant to wind turbines would reduce the most significant magnet design uncertainty. Other applications of superconducting magnets at temperatures above 10 K could move much farther into commercial markets due to the improved integrity and reliability of commercial magnet systems.

A major technical barrier is lack of experience with the operation and performance of superconducting coils operating at 5–77 K, whether conduction cooled or liquid cryogen cooled (other than liquid helium). R&D that results in a large number of coils with well-understood quench performance would be very useful. General development of quench modeling, detection, and protection would be an overall benefit. Development and availability of test beds suitable for performance testing of coils built by various groups (companies, universities, and national labs) would provide the much needed experience base for coil performance. Finally, demonstration of appropriate cryo-systems and testing of cryo-refrigerators are needed in harsh environments relevant to wind generators but outside conventional use. These systems are not normally subjected to such environments.

3.1.8 Barriers to Commercialization and Technology Introduction (Q6)

Focused development of magnet coils based on higher temperature superconductors (Nb_3Sn, MgB_2, Bi-2212, and ReBCO) will address most of the technical gap issues and indirectly drive characterization, development, and cost reduction of conductors. Encouraging adaptation of superconducting technology for other applications would also raise confidence. A reasonable program as part of a larger HEP magnet development program would require funding of about $2–5M/yr, assuming leveraging from existing conductor programs. Integration of the HEP magnet and wind generator R&D communities would be mutually beneficial.

3.1.9 Roadmap for Development (Q7)

It is important to keep in mind that manufacturers of wind turbine technology fit different solutions for wind farms to the specific conditions of sites. General advantages of superconducting turbines become part of a larger deployment portfolio, covering a fleet of turbine designs across several manufacturers. Advantages of one design over another are difficult to quantify prior to the completion of lengthy and detailed calculations, which themselves have considerable uncertainty due to unknowns in the emerging technologies.

Given this context, the following can be said about superconducting turbine technology:

- Development and refinement of different designs will be a continual process.
- Several combinations of field, temperature, refrigeration, and conductor selections could yield similar systems, for which competitive advantage will not emerge until after significant operational experience has been gained; LCOE will dictate the ultimate winner.

The successful closing of technical gaps identified earlier could result in basic understanding that provides multiple options for coil parameter choices, test beds and operational experience with various materials, conductor and magnet technology pipelines, and robust consumer-ready systems.

Power converters are an essential part of an electrical drive train for a wind turbine, especially for superconducting and PM machines, where full-power conversion is required. This issue is more limiting for turbines with superconducting armatures due to the AC losses in the conductor. These converters are significant contributors to the weight and cost of the drive train, which it is the goal to reduce. There is much overlap in power electronics technology between such high-power converters and the power supplies used by HEP. Therefore, efforts to increase the efficiency and reduce the weight of these converters should be of benefit both to wind farms and to HEP. Projects could be created to design advanced converters using the latest power electronic devices like SiC or GaN with the goal of higher efficiency, power density, and reliability. The projects could also support prototype construction as funds permit.

Similarly, control systems are constantly evolving in both their hardware platforms and software (algorithms); basic PID (proportional-integral-derivative) controllers are being displaced by more sophisticated model-based and model-predictive systems. These control systems are needed to optimize the LCOE of wind farms, and we have no doubt that control systems are also vital to sophisticated HEP facilities such as particle accelerators and synchrotron light sources.

Therefore, advanced control projects that are appropriately executed should benefit LCOE for both future wind farm and HEP facilities.

Realizing these goals could take place with sustained funding along the following roadmap:

1. Modest investment at the scale of $2M to $5M over the first 3 years in targeted development programs for coils and conductors.
2. Production of conductor and coil test beds, or extension of HEP test facilities, to study the field and temperature ranges where wind opportunities are available.
3. Demonstration of cryogenic systems with coils to establish reliability.
4. Integration of wind farm sub-systems in a pilot program.
5. Development of generic prototypes that are also synergistic with HEP. These should include required power electronic full-power converters and control systems.

3.2 Waste Separation

3.2.1 Background and State of Application Development (Q1)

Magnetic separators come in a wide variety but generally fall into two basic types: (a) open or continuous or (b) batch mesh/filter. An example of an open or continuous type familiar to the HEP community would be a quadrupole magnet, where magnetic field intensity varies as a function of $\cos(2\theta)$, referred to as high gradient magnetic separation (HGMS). The batch-type magnetic separator with a magnetic mesh/filter is probably the most common type with many variations, including both dry and wet/slurry types. The use of superconducting magnets for HGMS must be evaluated on a case-by-case basis. Typically, for HGMS to be effective, it is not important to use a very high magnetic field for magnetic separation, i.e., higher than the saturation field of iron, if the magnetic field gradient and particle seeding (if required) are appropriate. Superconducting magnets might make a difference, however, in the case of a process that requires a very high volume. In this case, large-bore superconducting magnets will win out over traditional electromagnets because of the electric power savings, and sometimes, because of reduced weight or volume, if transportability is required.

Dry-type magnetic separators are almost exclusively fabricated with permanent magnets. Most large-scale magnetic separators with >50 tons/hr processing capacity are fabricated with superconducting magnets. The first superconducting magnetic separator systems were fabricated using Nb-Ti systems cooled in a liquid helium bath, but this has slowly migrated to the reciprocator type using low-loss combination cryocoolers with liquid helium.

Considering the high level of current interest in energy efficiency, bio-processing, nanoparticles, and other burgeoning technologies, it is appropriate to review superconducting magnet technology in the light of new materials, cryogenics, and design practice. Of particular interest is operation at cryogenic temperatures much higher than liquid helium at 4.2 K, i.e., in the 20–50 K temperature range, using high temperature superconductors (HTSs), such as MgB_2, bismuth-strontium-calcium-copper oxide (BSCCO), and ReBCO. This results in increased efficiency and higher system reliability.

Among the earliest commercial uses of superconducting magnets was the replacement of large, resistive electromagnets for kaolin and china clay beneficiation.

Current technology, based on conventional and superconducting magnets, seems adequate for typical applications given the challenges associated with implementing superconducting systems. Existing costs are thus based upon Nb-Ti technology with low-loss liquid helium cryostats similar to those used for magnetic resonance imaging (MRI).

3.2.2 Regulatory Framework (Q2)

The use of superconducting technology should not result in additional regulatory issues beyond standard engineering requirements related to pressure vessel codes, welding codes, and hazardous material identifications (if any). Regulatory aspects are common to both conventional and superconducting technologies and are a strong function of environment and health regulations.

3.2.3 Economic Analysis (Q3)

Further developments in technology are not strongly needed, but demonstration of system performance and reliability and cost reduction could encourage adoption of the technology by industry. Switching from existing low temperature superconductors (NbTi-based liquid helium) to all conduction-cooled HTS systems would require:

- Conductor costs < $50 /kA-m (77 K, self-field) and a lift factor >5 at 20–30 K and 5 T,
- Abandonment of a pancake design approach and development of a safe, reliable, layer-wound coil methodology, and
- Development of a low-cost, highly reliable quench detection and protection methodology for HTS conduction cooled magnets.

3.2.4 Performance Criteria (Q3)

Now that HTS conductors such as Bi-2223, Bi-2212, MgB_2, and ReBCO are becoming more widely available, superconducting magnets might be able to play a larger role in separation applications, especially if the technology moves in the direction of magnet operation at higher temperature. Also, with the improvement of modern cryocooler technology, conduction cooled (so-called “dry”) magnets could be used, eliminating many of the disadvantages of providing liquid helium refrigeration in what is generally a harsh industrial or outside environment. DuPont was the first to introduce HTS magnetic separators for the purification of kaolin clay and TiO_2, but was never able to monetize these magnetic separation systems due to excessive costs of the HTS conductor and HTS magnet fabrication. Break-even costs of the HTS conductor needed to be lower than $50/kA-m (77 K, self-field) with lift factors >7 at 20 K and 5 T.

Costs of competing technologies will be discussed in the sections on using electron beams in wastewater streams. Filtration and chemical treatment are the main competitors. Magnetic separation is a significant way to enhance these other treatment systems. Cross-cutting research might be productive.

3.2.5 Technical Gaps (Q4)

The technical gaps are similar to those for any application of superconductivity and include overall system cost, operation complexity, and reliability. The lack of experience with superconducting systems is a significant barrier to further adoption and spread of the technology in this area.

3.2.6 Synergistic Application-Side R&D (Q5)

Magnetically enhanced solid-liquid separation would be of interest for industrial-scale applications of superconductivity. The tie to HEP is that a high-gradient quadrupole (>220 T/cm) type field would be of great benefit. While there is not a strong commercial case, "dry" cryogenic systems may be useful along with lower cost HTS conductors; safe, affordable quench detection and protection systems; and methods for faster heat transfer through lighter weight materials via conduction mechanisms rather than just addition of more Cu or Al material.

3.2.7 Required R&D to Bridge Technical Gaps (Q6)

For the waste separation application, R&D that results in a large number of coils with well-understood quench performance would be very useful. General development of quench modeling, detection, and protection would be an overall benefit. Development and availability of test beds suitable for performance testing of coils built by various groups (companies, universities, and national labs) would provide the much needed experience base for coil performance. Finally, demonstration of appropriate cryo-systems and testing of cryo-refrigerators are needed in harsh environments relevant to waste separation outside conventional use. One possibility suggested to help move the technology forward was to choose a waste remediation or separation process of interest to DOE, then perform the R&D to determine whether magnetic separation can play a relevant role.

3.2.8 Barriers to Commercialization and Technology Introduction (Q6)

Focused development of magnet coils based on HTS will address most of the technical gap issues and indirectly drive characterization, development, and cost reduction of conductors. Encouraging adaptation of superconducting technology for other applications would also raise confidence.

3.2.9 Roadmap for Development (Q7)

The successful closing of technical gaps identified above could result in basic understanding that provides multiple options for coil parameter choices; test beds and operational experience with various materials, conductor and magnet technology pipelines; and robust consumer-ready systems.

Realizing these goals could take place with sustained funding along the following road map:

1. Modest investment at the scale of $2M to $5M over the first 3 years in targeted development programs in coils and conductors.
2. Production of conductor and coil test beds, or extension of HEP test facilities, to study the field and temperature ranges where waste separation opportunities are available.
3. Demonstration of cryogenic systems with coils to establish reliability.
4. Demonstration of a fully integrated waste separation system in a pilot program.
5. Development of generic prototypes that are also synergistic with HEP.

3.3 Superconducting Transmission Lines and Load Leveling

3.3.1 Background and State of Application Development (Q1)

For over a decade, installation of new transmission lines has been a very uncommon occurrence. The development of overhead power transmission has almost disappeared as an option in the U.S. In part, this is due to an unfavorable investment environment, but in part, it is also due to the extreme difficulty in obtaining the necessary permits and rights of way. Until recently, the principal resistance was based on environmental and aesthetic concerns. In more recent years, the vulnerability of the transmission grid to hostile attack has become a widespread concern. The vulnerability of the power system to a cascading failure due to contact between overhead lines and trees has also been dramatically demonstrated.

The use of superconducting and cryogenic technology to increase the cost effectiveness, efficiency, and capacity of the power grid will greatly impact our present portfolio of power sources and may also be needed for large-scale implementation of renewable sources, such as wind and solar. Because of the intermittent nature of these sources, it is necessary to allow for increased capacity to cover the electricity needs during conditions when local electricity generation is unfavorable. In addition, underwater superconducting transmission lines are attractive to harness the electrical power generated by offshore windmills.

As a rule, power transmission by overhead lines is an order of magnitude less expensive than transmission by underground cable. If the construction of new overhead transmission lines remains an option, then new underground cables would be considered principally in dense urban areas and underwater. For superconducting cables, the tradeoff is between lower operating cost and higher capacity per installed circuit vs. lower capital cost for conventional cable. High temperature superconductor wire enables power transmission and distribution cables with three to five times the capacity of conventional underground AC cables and up to ten times the capacity of DC cables.

A possible solution then is to use DC transmission. The capacitance is not a dominant concern for relatively short distances as might be used to link wind farms and the power grid. However, the cost of conversion at the ends of the line becomes important. Direct current transmission also favors high temperature superconductor cables, whose cryogenic loads are dominated by AC losses at 60 Hz. Extensive system expansion using high-voltage DC underground or undersea cables is a scenario that has not been adequately examined. This scenario is, therefore, a useful area for research and an opportunity for superconducting transmission.

Significant development of superconducting AC transmission lines has been undertaken over the past decade in the U.S., Europe, Russia, Korea, China, and Japan. Direct current transmission lines are gaining in popularity, and some demonstration projects have been done in Japan, China, and Russia, but the application of superconductivity to DC transmission lines may offer significant advantages for long distance transmission and for short range power distribution.

Among these advantages are:

- No DC resistive losses
- No AC inductive storage
- Negligible AC losses (due only to harmonic ripple)
- Long range transmission of high currents, including undersea
- Very high power ratings, including transmission of several GVA
- Fault currents limited by fast acting inverters at AC/DC and DC/AC ends of the line
- Low voltage transmission, if desired, limiting the need for high voltage transformers
- Simplified cable design, compatible with HTS tape geometry
- Cryogenic cable coolant available to cool solid-state inverters, increasing capacity and reducing high-temperature aging degradation

The disadvantages of this approach include:

- Cost and maintenance of power conversion rectifiers and inverters
- Flashover faults at terminals, leading to loss of superconductivity and burnout
- Long length distribution that requires adequately spaced intermediate cooling stations

Development of superconducting transmission lines has been pursued fairly extensively but so far has not proven economically viable in most grid applications. However, as part of an offshore superconducting wind farm where the cryogenic infrastructure already exists, it could prove feasible. Another look at superconducting magnetic energy storage for load leveling might be appropriate. The focus of recent R&D has been on AC applications for short length (e.g., urban, high power density) use. There is persistent but low level interest in DC transmission for which superconducting cables have advantages but no DC demonstrator base equivalent to the AC demonstrator base exists. The technology for power distribution is undecided and an area of R&D. Power converters and controls are an important aspect of transmission and are also an object of current R&D. Cryogenic electronics are occasionally considered as an efficiency improvement for semiconductor power converters and align well with superconducting machines because of the cryogenics.

3.3.2 Regulatory Framework (Q2)

Regulators are beginning to require control of reactive and active power and to require low voltage ride-through. Wind farms are subject to FERC (Federal Energy Regulatory Commission) and State equivalents.

3.3.3 Economic Analysis (Q3)

Better understanding of cryogenic systems in the 10 W–1 kW range across the superconducting temperature range could lead to more accurate cost models. Direct current cable development could contribute to interconnect technology among other technologies. Direct current distribution can take some of the power electronics off the individual turbine towers. Overall, wind farm architecture, controls, and power converters are important in this topic.

3.3.4 Performance Criteria (Q3)

Wind generator power output is variable in time and often intermittent. Power output from the generator is variable frequency AC, which must go through a power converter to DC and then through a power inverter to convert to the fixed (grid) frequency AC. When a system goes from offline to online, the output power must be synchronized to grid frequency before connecting. There could be significant advantages to eliminating the DC-to-AC inverter on the tower and just interconnecting all generators through DC links. This eliminates a part of the power conditioning system on the wind towers and allows for much easier variable power flow onto a DC bus. The power is collected from all generators and transmitted to a single power inverter for final conversion to grid frequency and voltage transformation (if necessary) and connection to the local power grid.

3.3.5 Technical Gaps (Q4)

The largest technical gap is lack of long-length, high-critical-current transposed cables at low cost. Other gaps include the need to develop robust power cable flexible cryostats in long lengths suitable for underground or undersea use, as well as reliable methods for cryogenic cooling of the various power distribution cables. If the wind generator is superconducting, then there will be cryogenic infrastructure available at each wind tower, and an efficient cryogenic circuit needs to be developed.

Another technical requirement would be the need to develop highly reliable cable and cryostat terminations and connections capable of being connected in the difficult field environment, including undersea, without the need for sophisticated tooling or equipment (e.g., vacuum systems, welding stations, etc.).

Research and development aimed at more efficient and lower cost power converters for wind farms is likely to favorably impact the many power supplies needed by HEP in cost, reliability, capability, and power density. An outstanding example is SiC device and equipment development.

3.3.6 Synergistic Application-Side R&D (Q5)

Deployment of HTS conductors is vital to realize superconducting cables for high power interconnects between generators and between the wind farm and the grid.

Development of SiC devices, needed for the required wind converters, will synergistically benefit most HEP power supplies.

Development of this technology for relatively short-distance (~100 m to ~1000 m) power distribution could lead to much wider scale adoption of DC power distribution systems, including microgrids and power islands. This development would be especially advantageous because of the increasing need for integration of DC or variable AC and intermittent renewable power sources to the grid (e.g., solar photovoltaics, fuel cells, and microturbines).

Success in these developments could lead to direct application of long-length DC power distribution systems for large-scale HEP accelerators, e.g., Large Hadron Collider upgrade, a Future Circular Collider, etc.

3.3.7 Required R&D to Bridge Technical Gaps (Q6)

Continued development of HTS cable technologies, including reliable ReBCO splices, and R&D of SiC devices for advanced power supplies/converters would be a helpful extrapolation of HEP development. This work would need to be supported by R&D of DC mini-grids for wind farms.

Also needed is R&D on lowering the cost of flexible, long length cryostats, with heat leak minimization, as well as development of efficient cryogenic cooling methods and refrigeration technology for cooling below liquid nitrogen temperature (<65 K).

3.3.8 Barriers to Commercialization and Technology Introduction (Q6)

Lack of experience with superconducting systems, including overall cost and reliability, could be addressed indirectly through extrapolation of HEP development. Additional R&D is needed to assure that the technology is available to meet regulator (FERC and State) demands.

3.3.9 Roadmap for Development (Q7)

The basis of an R&D development roadmap would primarily be defined by evolving HEP needs and could be effectively leverage and broadened with a modest investment of $1–$2M/yr.

3.4 Superconducting Materials (Cross-Cutting)

3.4.1 Background and State of Application Development (Q1)

Superconducting materials are key to successful development of all the above technologies as well as future HEP accelerators. The development of superconducting magnet technology for particle accelerators and fusion machines has driven the development of long-length, multifilament, twisted strand conductors from Nb-Ti and Nb_3Sn, where production capabilities are on the order of 1000 tons per year for Nb-Ti and 50 tons per year for Nb_3Sn. The persistent market demand for MRI machines has kept the cost of Nb-Ti conductors at a commodity level, around $2 per meter for wire approximately 1 mm in diameter and rated at 1 kA. Costs of Nb_3Sn conductors can be higher by a factor of ~5, where physics applications impose a stringent combination of specifications. These materials form the backbone of practically all magnet technology.

The technology for HEP magnets is presently focused at ~2–6 K and 12–16 T, somewhat different than the parameter space for the energy and environment opportunities discussed in the preceding sections. The high temperature superconductors Bi-2223, ReBCO, and Bi-2212 show the way to more than 30 T at 4 K. Both ReBCO and Bi-2223 cable can be obtained in forms ready for the winding of magnets without final treatments, but also come with the drawbacks of large-aspect-ratio, anisotropic tapes. They both require sophisticated production lines that require high capital investments, and cabling approaches are different than those traditionally used by HEP. By contrast, Bi-2212 cable is simpler to manufacture and is round, twisted, and multifilament, from which Rutherford cables can be manufactured. But the wound magnet must be subjected to a high-pressure treatment in a very narrow temperature range, which so far has not been possible to realize for coils of significant size. All three HTS's are expensive, on the order of 5 times the cost per meter of Nb_3Sn and as much as 25 times the cost per meter of Nb-Ti conductors.

The materials outside of the niobium family also permit multi-tesla fields well above 4 K, in the temperature range of interest for energy and environment applications. To date, HEP has not generally explored magnet applications in this area. In addition to the cuprate conductors above, MgB_2 (T_c is 35–38 K in conductors) has inexpensive raw materials but does not yet challenge high-field HEP applications seriously due to a critical field of only 5–15 T at 4 K, even though upper critical field (H_{c2}) values of over 40 T have been demonstrated in thin films. This material is quite capable of 0.5–3.0 T fields at 20 K, an application presently being exploited for MRI magnets. A new material, $(Ba_{0.6}K_{0.4})Fe_2As_2$ (K-122), also has a T_c = 38 K and cheap raw materials and very high H_{c2}, >80 T at 4 K, but has yet to be demonstrated in long-length multifilament wires. It is promising that K-122 in untextured form can achieve a critical current within about a factor of 5 of that needed for applications, with much higher values being obtained when texture is created in tapes by using processes like those used to make ReBCO.

3.4.2 Regulatory Framework (Q2)

The selection of superconducting materials is not subject to regulatory or political frameworks. Production takes place at many companies on an international scale, and procurements from offshore suppliers may be subject to rules normally applied to other imported goods.

3.4.3 Economic and Performance Analyses (Q3)

Economic and performance indices are often linked. The metric for magnet conductor procurement is ampere-turns, so the unit of $/kA-m is commonly used to describe the value of a conductor. Thus, it is possible to offset a high cost per unit length by achieving a higher performance. While for HEP applications this offset is generally difficult to do, because the application temperature is fixed at ~4 K, energy and environment applications offer significant flexibility across 10–60 K. Superconducting properties generally improve with reduction of temperature, relative to T_c, and of field, relative to H_{c2}, with characteristic scaling exponents that depend on the material and its underlying physics. Since the field-temperature space increases with reduction of temperature, the performance improvement exponent is generally greater than, and sometimes much greater than, 1.0. This implies cost-performance minima at intermediate temperatures, above the point where cryogenic costs become prohibitive.

Magnet technology generally requires a performance of >500 A/mm^2 across the wire cross section. Efficient racetrack magnets can be wound with lower current density, but the cost of additional conductor turns will generally prohibit conductors with lower capacity unless the cost per meter is very low.

Specifications for magnet conductors often call out additional performance criteria, which are related to the functional requirements of the magnet. These may include 1) the amount of copper, silver, aluminum, or another material used for the stabilizer; 2) the dimension(s) of the superconducting filament; 3) the DC magnetization produced by the conductor; 4) the dynamic or AC loss produced by the conductor; 5) the resistivity or conductivity of the stabilizer; 6) the minimum length of supplied conductor pieces; 7) the mechanical properties of the conductor; and 8) other materials or conditions used in conjunction with the conductor, such as insulation. Often, performance criteria are linked, such as the stabilizer resistivity and the AC loss.

3.4.4 Technical Gaps (Q4)

Superconducting materials for energy and environmental applications are confronted by the technical gaps shown in Table 3-1.

Table 3-1 Technical gaps for superconducting materials.

Gap	Nb_3Sn	Bi-2212	Bi-2223	ReBCO	MgB_2
Cost above $10/m		X	X	X	
Lack of detailed performance information at 10–60 K, 2–8 T	X	X	Some	Some	Other than 20 K
Long-length transposed cables			X	X	
Reliable joints and splices		X	X	X	X
Sensitivity to strain	X	X	X		Unknown

3.4.5 Required R&D to Bridge Technical Gaps (Q6)

Required to bridge the technical gaps is a targeted magnet conductor.

a. *Summary*: Programs in HEP conductor development have a past track record of producing performance gains by a factor of ~two in industrial production over a decade of focused R&D. A tight loop, connecting wire manufacturers, magnet developers in national laboratories and in manufacturers of equipment, and materials scientists in university groups, is the central dynamic that has been exploited to achieve these gains.

b. *Research Directions*:

   i. *Prove conductor innovations in magnets*: The main conductors in the HEP portfolio also comprise the main conductors for energy and environmental applications, with the possible exception of MgB_2. Research directions should incorporate magnet testing in the 10–60 K, 2–8 T range for energy applications.

   ii. *Obtain basic conductor information at temperatures above 4 K*: This research direction reiterates a recommended direction for Section 3.1.7. The body of information about properties of magnet conductors at temperatures other than 4.2 or 77 K is generally inadequate for magnet development. Measurements of properties as functions of field, temperature, and strain should yield scaling relationships that can reliably predict performance relevant for magnet technology. Since magnetometers can more rapidly search this parameter space than transport measurements, the methodology for connecting magnetization measurements to transport data, especially for strongly inter-connected conductors, needs further development. For flat conductors, measurement of properties as function of field angle to the surface is important.

c. *Challenges*: Magnet engineers do not have extensive experience with conductors other than those based on niobium. Tests may require conduction cooling, which may require modification of facilities and cryogenic engineering for support infrastructure. While in principle the infrastructure used to fabricate coils for operation at 4.2 K can also be used for coils operating at other temperatures, research activities could instigate changes in instrumentation, power supplies, materials, and tooling. New test probes and measurement techniques may be required. Candid discussions about the weaknesses of innovations must accompany the discussion of positive outcomes.

d. *Potential impact*: Conductor innovations over an extended period could lead to cost reduction, performance improvement, and resolution of gaps. Focus on evaluation in actual magnets assures relevance of innovations for both HEP and for energy and environment applications. Characterization by academic groups will provide basic understanding, which will catalyze further innovation and improvements.

3.4.6 Roadmap for Development (Q7)

The HEP community maintains a vigorous conductor development program, including research programs at universities and the magnet development programs at the national laboratories. To facilitate conductor development for energy, the scope of conductor development could be expanded to include the parameter space important for energy applications. This includes development of scaling rules, anchored by property measurements at 8–60 K and 2–8 T field.

A second component of the roadmap could be to leverage the ability of small business to perform targeted conductor R&D for energy applications. The HEP community benefits from innovations that lead to longer pieces, higher manufacturing yield, higher current density, better stability, and other properties relevant to magnet technology in the parameter space for applications for energy and the environment. An underpinning of this benefit is the fact that superconducting properties have well defined behavior as functions of field and temperature, making improvements at high temperatures also relevant for ~4 K, where HEP applications are located. The magnet technology community has begun to engage with this topic, and there are clear examples where HEP magnet application experience has influenced the context of discussions. An example is "lift factor," a temperature scaling concept applied to ReBCO, which has been refined to directly address the needs of energy conductors.

A third step along the roadmap should be to augment test facilities that add capabilities at higher temperatures. Many contactless methods exist for small lengths, a few millimeters, of wire using vapor-cooled environments to measure magnetization and transport properties. However, transport measurements over 1-m lengths of wire are quite difficult due to the problems associated with thermal gradients, current leads, contact voltages, and the large currents carried by 1-mm diameter conductors of high quality. National Institute of Standards and Technology (Boulder) demonstrated kiloampere-class measurements at variable temperatures for fusion science, and these techniques should be adapted to higher temperatures. Methods to continuously sample the critical current as a function of length for ReBCO were developed at Los Alamos National Laboratory for use at 77 K, and were recently adapted for use at ~4 K. Connecting these very detailed measurements to the 10–60 K regime will require innovations in the measurement system.

As an example of the type of property scaling information, Nb_3Sn has undergone very detailed analyses as functions of temperature, field, and strain. The information detail is such that it is possible to parameterize behavior across the full region of its superconducting state. Magnets can be fully engineered for the 8–12 K range, and it may be an important test along this roadmap to design, build, and test Nb_3Sn coils in this range to validate this approach. Expanded scaling information for emerging conductors should facilitate the engineering of coils at the higher temperatures.

4. Summary of Findings and Research Needs

The *Workshop on Energy and Environmental Applications of Accelerators* identified a broad spectrum of research needs to move electron beam and superconducting technology from an innovative technology to one that is truly disruptive in the environmental and energy marketplace. Because of the broad scope of applications considered, and the diversity of workshop attendees, the resultant list of research needs was wide-ranging and, in many cases, overlapping between applications. The identified basic research needs are summarized below in terms of (i) immediate science-based needs (i.e., discovery research and use-inspired basic research) and (ii) synergistic application-side needs.

4.1 Immediate (Near-Term) Science-Based Research Needs

Applications of Electron Beams

- Develop the science needed to evaluate and define E&E accelerator applications to overcome short-term show stoppers.
- Conduct basic research to develop a fundamental understanding of the effect of electron beam technology on the "Grand Challenge of Sustainable Environmental and Energy Applications."

Accelerator Technology

- Advance technologies to overcome limitations in high power electron beams:
    - Improve reliability, beam power, and performance of DC accelerator systems.
    - Optimize linear accelerator systems for low-energy, high-beam power operation.
    - Understand and overcome beam dynamics limitations of ampere-class beams in the 1–10 MeV range.
    - Develop more reliable and efficient RF power sources and delivery systems suitable for >1 MW applications.
- Develop electron beam technology to extend the beam power reach by more than one order of magnitude beyond today's capabilities at 1 and 10 MeV.

Electron Beam Systems Engineering

- Develop science-based predictive models of the total energy footprint for new electron beam systems.
- Develop predictive science-based models to optimize new electron-beam system geometries, considering accelerator voltage, current, vacuum containment, and shielding materials.

Radiation Chemistry and Irradiation Studies

- Develop science-based predictive models to understand radical yield from irradiated aqueous streams as modified by environmental parameters.
- Develop predictive science-based models of fundamental changes in wastewater due to electron beam irradiation.
- Develop focused science-based predictive models of medical (hospital) waste sterilization to allow landfilling. Unique cost/energy advantages of electron beam technology will aid to overcome short-term show stoppers.

- Gain fundamental understanding of the chemistry of electron beam irradiation of hydrocarbons in the environment.
- Gain fundamental understanding of advanced, real-time, in-situ imaging concepts to optimize electron dose distribution in mixed-density, nonaqueous wastes.

Superconducting Systems

- Gain fundamental understanding of the operation of high temperature superconducting coils in the temperature range between boiling liquid helium and liquid nitrogen.
- Develop a basic understanding of stability, quench, and other origins of magnet failure when operated at temperatures above 10 K.
- Gain understanding and demonstrate cryogen-free magnet systems.
- Develop magnet coils based on high temperature superconductors.
- Conduct R&D on SiC devices for advanced power supplies/converters.
- Conduct R&D on lowering the cost of flexible, long-length cryostats with minimal heat leak and develop efficient cooling methods for cooling below liquid nitrogen temperatures.
- Gain fundamental understanding of conductor performance and properties above 4 K.
- Coordinate, leverage, and work with researchers in other programs pursuing synergistic R&D.

4.2 Synergistic and Applied Research (Longer Term)

- Develop complete electron beam systems that demonstrate higher beam power with reduced capital costs, increased reliability, and improved efficiency.
- Demonstrate proof of technology at large scale in actual environmental application in conjunction with major potential users and societies.
- Develop training formats and educational programs on electron beam applications for the environmental engineering profession.
- Launch focused program to build and test magnets in the 10–60 K, 2–8 T range.

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Appendix A

A.1 List of Participants

Table A-1 Invited Participants

Name	Affiliation
Lance Cooley	FNAL
Bill Cooper (#)	U.C. Irvine
Charlie Cooper	Fermilab
Randy Curry	U Missouri
Ralf Eichhorn	Cornell University
Shrirang Golhar	Dallas Water Utilities
Steve Gourlay (#)	LBNL
Thomas Granato	MWRD Chicago
Stuart Henderson (*)	Argonne
Jay Hirshfield	Yale University
Mark Kemp	SLAC
Tom Kroc	Fermilab
David Larbelestier	FSU
Philippe Masson	U Houston
Peter McIntyre	TAMU
Daniel Meeroff	Florida Atlantic University
Joe Minervini	MIT
Jerry Nolen	ANL
Peter Ostroumov	ANL
Suresh Pillai (#)	TAMU
John Power	ANL
Bob Rimmer	JLab
David Staack	TAMU
Paul Tornatore	Haley & Aldrich (retired)
Tom Waite (*)	Florida Institute of Technology
Slava Yakovlev	Fermilab

(*) Co-chairs
(#) Organizing Committee Members

Table A-2 Other Participants

Name	Affiliation
Jim Bray (&)	GE
Bob Brobst (%)	EPA
David Brown (&)	Mevex
Andrzej Chmielewski ($)	Inst. Nuc. Chem. Tech., Poland
Eric Colby	DOE
Joe Cotruvo ($)	EPA
Rick Galloway (&)	IBA
Terry Grimm (&)	Niowave
Robert Hamm ($)	R&M Tech. Enterprises
Bumsoo Han (%)	EB Tech
Selim Hoboy (%)	Stericycle
Mark Johnson	DOE
Tina Lerke (%)	ONR
Ken Marken	DOE
Ken Olsen	DOE (Consultant)
Chris Rey (&)	Tai Yang Res. Company
Sunil Sabharwal (%)	IAEA
Jim Smith ($)	EPA
Alan Todd (%)	Advanced Energy Systems
Mike Tomsic (&)	Hyper Tech Research Inc

(&) Observers
(%) Remote Observers
($) Remote Contributors

A.2 Workshop Charge

DOE Workshop on Accelerator Applications in Energy and Environment

BACKGROUND
The Office of High Energy Physics, as DOE's host office for the Accelerator Stewardship Program, is conducting a Basic Research Needs (BRN) workshop to assess R&D needed to enable high-impact applications of accelerator technology to address Energy & Environmental (E&E) challenges. Responses to a 2014 Request for Information identified two major technology areas as having highest promise for (1) near-term impact (<5 year), such as accelerator-related technologies for efficient manufacturing and superconducting generators, and (2) medium-term impact (<10 years), such as medium- and high-power electron beam accelerators.

Present and proposed uses for accelerator technology in E&E applications include: treating potable and waste water, removing pollutants from stack gases, increasing the energy efficiency of industrial material processing, increasing the capacity of wind generators, enhancing magnetic separation of material streams, and replacing radioactive sources in sterilization and environmental monitoring applications. In many cases the use of accelerator technology for these

applications has performance advantages. However the barriers to significant commercial deployment of accelerator technology include cost, wall plug efficiency, reliability, regulatory approval, and end user resistance to the risk inherent in changing technology. Many of these energy and environmental applications are currently met by existing, well proven technologies; however, recent improvements in accelerator technology has lowered the cost and increased the reliability of these accelerators for energy and environmental applications.
This BRN workshop will identify opportunities and barriers to market adoption in the two technology areas noted above. The goal is to identify accelerator technology R&D opportunities that, if developed, could enable high-impact solutions for current E&E challenges.

Attendance at the workshop is limited and will be invitation.

WORKSHOP CHARGE
DOE OHEP has been gathering and reviewing information on several energy and environment application areas for accelerator technology. The BRN workshop will be asked to:

- Assess the state of any existing accelerator and non-accelerator based technology currently deployed for the application. Document cost and performance criteria to be used as a baseline for alternatives utilizing accelerator based technology.
- Document current and proposed Federal and State environment, safety, and health regulatory requirements for the application and identify any issues with regard to these regulations.
- Develop criteria for accelerator based systems for the application. Consider total system costs for production and operation. Assess the potential financial and/or environmental impacts if the accelerator technology meets the criteria. Document specifications for the accelerator component of the system.
- Identify technical gaps between the current state of the art of accelerator technology compared to the above specifications. This may include accelerator-related technologies such as power supplies or magnet technology.
- Identify synergistic application-side R&D relevant to the application of accelerator technology to E&E challenges.
- Specify R&D activities needed to bridge technical gaps, and any environmental analysis and testing required to approve their use
- Develop a list of R&D and regulatory compliance issues, include first order funding estimates

The workshop outcome will consist of a concise report describing high-impact opportunities for accelerator technology to impact E&E challenges, the needed accelerator R&D to address these challenges. The report should include an R&D roadmap, with particular attention given to technology transfer to industry.

A.3 Glossary of Abbreviations

AC – alternating current
AEP – annual energy production

BRN – basic research needs
BSCCO – bismuth-strontium-calcium-copper-oxide

CAPEX – capital expense
CEBAF – Continuous Electron Beam Accelerator Facility
CESR – Cornell Electron-positron Storage Ring
COTS – commercial off the shelf
CPI – Communications & Power Industries
CW – continuous wave
DC – direct current

DD – direct drive
DOE – Department of Energy
DOT – Department of Transportation
DTPD – dry ton per day

E&E – energy and environment
EBFGT – electron beam flue gas treatment
EPA – Environmental Protection Agency
ERL – Energy Recovery Linac
ESP – electrostatic precipitator

FERC – Federal Energy Research Commission
FGD – flue gas desulfurization
FHWA – Federal Highway Association

HEP – high energy physics
HGMS – high gradient magnetic separation
HOM – higher order mode
HTS – high temperature superconductor
HV – high voltage

IAEA – International Atomic Energy Agency
IOT – inductive output tube

LCLS – Linac Coherent Light Source
LCOE – levelized cost of energy

MGD – million gallons per day
MRI – magnetic resonance imaging
MW – megawatt

NCRF – normal conducting radio-frequency
NIST – National Institute of Standards and Technology
NREL – National Renewable Energy Laboratory
NSF – National Science Foundation

OPEX – operating expense

PM – permanent magnet

ReBCO – rare-earth barium copper oxide
RF – Radiofrequency
RFI – Request for Information
RMB – radiation modified binder

SBIR – Small Business Innovation Research
SC - superconducting
SCR – selective catalytic reduction
SLAC – Stanford Linear Accelerator
SNCR – selective non-catalytic reduction
SRF – superconducting radiofrequency
SSA – solid state amplifiers
STTR – Small Business Technology Transfer

TPH – total petroleum hydrogen

VAR – vector attraction reduction

XFEL – X-ray Free Electron Light Source