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Information needs for siting new, and evaluating current, nuclear facilities: ecology, fate and transport, and human health

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Abstract The USA is entering an era of energy diversity, and increasing nuclear capacity and concerns focus on accidents, security, waste, and pollution. Physical buffers that separate outsiders from nuclear facilities often support important natural ecosystems but may contain contaminants. The US Nuclear Regulatory Commission (NRC) licenses nuclear reactors; the applicant provides environmental assessments that serve as the basis for Environmental Impact Statements developed by NRC. We provide a template for the types of information needed for safe siting of nuclear facilities with buffers in three categories: ecological, fate and transport, and human health information that can be used for risk evaluations. Each item on the lists is an indicator for evaluation, and individual indicators can be selected for specific region. Ecological information needs include biodiversity (species, populations, communities) and structure and functioning of ecosystems, habitats, and landscapes, in addition to common, abundant, and unique species and endangered and rare ones. The key variables of fate and transport are sources of release for radionuclides and other chemicals, nature of releases (atmospheric vapors, subsurface liquids), features, and properties of environmental media (wind speed, direction and atmospheric stability, hydraulic gradient, hydraulic conductivity, groundwater chemistry). Human health aspects include receptor populations (demography, density, dispersion, and distance), potential pathways (drinking water sources, gardening, fishing), and exposure opportunities (lifestyle activities). For each of the three types of information needs, we expect that only a few of the indicators will be applicable to a particular site and that stakeholders should agree on a site-specific suite.

Keywords Nuclear facilities · Nuclear power · Monitoring buffers

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Introduction

The USA and the World are moving toward complex and diversified means of producing energy for the growing demands of both developed and developing nations. These needs relate to increasing populations and growing per capita demand for energy (Sheffield 1998). Oil reserves are limited and vulnerable to production quotas, and the US dependency on foreign oil at a time when oil production is unstable, costly, and vulnerable to political manipulation has long been recognized (Alm 1981). Energy diversification may be the key to fulfilling growing energy needs, and nuclear power is only one energy source. While other nations have moved toward greater use of nuclear energy, the US nuclear industry has remained static for several decades but is poised to move forward with construction of additional new reactors on existing sites and the possible siting of new reactors on previously unused sites. Despite a hiatus of over 30 years without the construction of any new domestic nuclear power plants, the Nuclear Regulatory Commission has recently received over 15 applications for nearly 30 reactors (NRC 2008). During this 30-year period, graduate training opportunities in health physics and radiation science, protection, and engineering have declined, training programs have closed, and the USA has lost many of the professionals versed in an understanding of the environmental regulations and requirements for siting new nuclear facilities (Walter 2004; IAEA 2004, 2006), despite increased needs in the medical radiology field (Bhargavan 2008). With increases in siting and construction of nuclear power plants in the USA, China, and elsewhere in the world, there is a clear need for environmental monitoring and assessment around these facilities.

Many of the complex problems surrounding increased nuclear energy production involve heated controversy, such as the remediation and restoration of Department of Energy nuclear sites and the siting of new nuclear power-generating facilities in the USA and elsewhere in the world. The controversies occur over the definition of the problem, alternative land use interests, characterization data, remediation decisions, restoration options, and the long-term protection of both human and ecological health around existing and proposed facilities (Greenberg et al. 2005; Burger 2007a, b). Environmental assessment (or evaluation) of potential sites for energy-producing facilities is critical for protecting human health and the environment around such facilities, as well as providing peace of mind to site neighbors (Cairns 1994; NRC 1986; Bartell et al. 1992; Cairns and Niederlehner 1996; Cairns et al. 1992; Barnthouse 1994; Suter 2001; Burger 2007c; Burger et al. 2007a, b). Environmental assessment includes characterization and evaluation of the physical, biological, and contamination aspects of the site.

Site characterization is not only critical for siting new facilities at new sites but it is also important and legally mandated for siting additional facilities on properties that currently hold nuclear power plants. While many of the environmental assessment approaches that served the nation in the past involved environmental protection laws, regulations, and top–down decisions, this approach may no longer work. The science, and the eventual solutions, may require more broadly based characterizations of the contaminants of concern, the resources at risk (both ecological and cultural), fate and transport (and exposure pathways), and the inclusion of a wide range of stakeholders (PCCRARM 1997; Goldstein et al. 2000; Harris and Harper 2000; Burger et al. 2003, 2007c; Stumpff 2006). In this context, we use stakeholders very broadly to include Native Americans, regulators, local governments, managers, public policy makers, scientists, conservationists, involved and affected citizens, and others of the public, although we recognize that Native Americans have a Sovereign Nation status (Nez Perce Tribe 2003) and unique ecological, cultural, and exposure information needs (Tano et al. 1996; Harris and Harper 2000).

Requirements for environmental assessment for nuclear reactors are set by the Nuclear Regulatory Commission in the US and other agencies in other countries. The licensing of new nuclear reactors (regardless of whether they are on existing sites on new brownfields or greenfields) in the USA includes the original licensing procedures and recent modifications (NRC: 10 CFR Part 52), as well as environmental assessments required by these new modifications and approaches. Although most applications are for siting new plants on sites that already have nuclear power plants, there is at least one application for a greenfields site (NRC website); there likely will be more in the future. While the applicant for siting of a new nuclear reactor (whether on an existing site or a new site) writes the environmental assessment, the Nuclear Regulatory Commission writes the Environmental Impact Statement. The Environmental Impact Statement process is broad, but not comprehensive, and does not provide the breadth of information nor assurance that stakeholders, local governments, and other regulatory agencies have come to expect in the 40 years since the National Environmental Policy Act (NEPA) of 1969. The public and the Nation, as well as NRC and the industry, will be served more effectively by addressing a broader array of environmental information needs than that required by NEPA, including information that relates directly to eco-receptors, fate and transport, and human health considerations.

We suggest that there should be a formalized template of information required to adequately characterize a site to ensure the protection of human health and the environment and that this template should be useful for a wide range of sites with potential contamination, including current US Department of Energy (USDOE) and Department of Defense lands, current nuclear power plants, and future sites for nuclear power plants, as well as other countries throughout the world. When formalized, these characterizations (or lists of variables) can serve as indicators for the sustainable protection of human health and the environment.

In this paper, we propose templates for assessing and monitoring (characterizations) for ecology, fate and transport, and human health. Adoption of such a template should prepare facilities to put monitoring systems in place and implement appropriate and effective mitigation measures when releases do occur. The relatively recent findings of tritium in the groundwater around some reactors due to releases from spent fuel pools and vacuum breakers on discharge lines caught the industry and the NRC by surprise, and characterization systems had to be installed post-release (NRC Liquid Radioactive Release Lessons Learned Task Force Report, September, 2006).

Sustainability poses another challenge for contaminated sites and associated buffer lands—can human and ecological health be protected over time, given the degree of possible contamination at chemical plants, nuclear facilities, and future nuclear power plants? To be sustainable, an ecosystem must have appropriate structure and functions that can continue to provide ecological goods and services for the foreseeable future (Leitao and Ahern 2002), as well as eco-cultural attributes (Burger et al. 2008). In this paper, ecosystem refers to the abiotic and biotic structure and function within the system. Ecosystem function refers to having complex food webs, nutrient cycling, energy flow, appropriate biodiversity, predator–prey relationships, and overall complexity, with appropriate feedback loops and resiliency (able to recover from natural or non-natural disasters or perturbations), among other characteristics (Sheehan 1984; Hunsaker et al. 1990; Cury et al. 2005).

The definition of sustainability approved by the United Nations Food and Agriculture Council in 1988 is that sustainability is the management and conservation of natural resources, and the orientation of technological and institutional change, to ensure the continuous satisfaction of human needs for present and future generations (Cena 1999). A second definition is that sustainability is meeting the needs of the present without compromising the ability of future generations to meet their own needs (UN 2008). In both definitions, "needs" remains undefined. In some definitions, the sustainable ecosystem continues to have appropriate species composition, structure, and productivity. We also suggest that another dimension of sustainability is the protection of cultural, medicinal, and aesthetic needs of Native American cultures and subsistence cultures (Whalen 1971; Norton 1995; Bingham et al. 1995; Costanza et al. 1997; Zender et al. 2004; Soderqvist et al. 2005). The template provided in this paper is aimed at providing the information to sustain or maintain ecological buffers around contaminated sites, particularly nuclear facilities, although they are applicable to other sites as well.

The question of sustainability in the long term is particularly important for nuclear or chemical wastes that cannot be remediated and will require safe storage in perpetuity (USDOE 1999, 2001), perhaps long after the productive lifespan of the plant itself. In general, the cleanup at USDOE sites will not have removed most of the long-lived radioactive and hazardous contaminants, necessitating long-term stewardship into the indefinite future (USDOE 1999, 2000; Crowley and Ahearne 2002). The task of remediation, restoration, and long-term stewardship on these lands is particularly daunting for agencies that hold numerous, large tracts of land, such as USDOE and USDOD, and public fears about these wastes have fueled concern for the siting of nuclear power plants (NRC 2000). Nuclear power plants in the private sector similarly have spent nuclear fuel in pools and dry cask storage, and efforts to locate long-term or even interim storage or to develop reprocessing for commercial spent nuclear fuel have been unsuccessful (Kosson and Powers 2008).

The siting of new nuclear power plants is difficult precisely because of the resistance of local and regional residents and the overall fear US residents have of nuclear accidents and nuclear waste (Slovic 1987; Kunreuther et al. 1990; Flynn et al. 1994; Burger 2004; Greenberg et al. 2002). However, in some places, this may be changing (Greenberg et al. 2007), and views differ depending upon how far people live from the site. An international poll conducted by the consulting firm Accenture over 20 nations reported on March 17, 2009 that "29% of 10,518 respondents favor increased use of nuclear power outright and an additional 40 would support the expansion of nuclear power if their concerns were addressed". In USA, 37% of the respondents said they supported more nuclear power, and an additional 41% would support an expansion of nuclear power if their concerns were "overcome." On March 20, 2009, the Gallup Organization reported that they had conducted a telephone poll and that 59% of the 1,012 respondents favor nuclear power as one of the ways to provide electricity for the USA, up from 57% in 2007 (Nuclear News 2009).

Partly, the characterization or assessment task is difficult because of the complexity of ecosystems, with thousands of species (including microorganisms), complex interactions and levels of organization (species, populations, communities, ecosystems, landscapes) (Burger 2007b), and the multiple pathways of exposure. The task is also difficult because many of the potential sites for new nuclear power plants, including existing commercial sites where new facilities could be located, are either near human population centers or in areas deemed ecologically sensitive. This is true as well for some of the large USDOE sites, which have many different habitats and ecosystem types (Dale and Parr 1998; Burger et al. 2003; Whicker et al. 2004). Recognizing the complexities posed by proximity to population centers, presence of endangered, threatened species or ecosystems, or unique and rare habitats will facilitate the development of facilities with minimal impact on ecological or human health.

This paper addresses the problem of characterization required to protect humans and the environment by providing a template of information needs for understanding risk at present nuclear facilities and new sites proposed for nuclear power plants. Such indicators are essential to provide Native Americans and stakeholders with sufficient information to make sound decisions, as well as for uniformity, consistency, and usefulness of the indicators (Hart 1999). There are methods of assessing the characteristics of human communities surrounding hazardous facilities and waste sites, and these can produce models that integrate human behavior and lifestyles (Heitgerd and Lee 2003), as well as Native American exposure scenarios (Harris and Harper 2000). Using the literature and our own combined experience for more than 25 years working at hazardous waste sites including 14 years experience each working at USDOE environmental management sites, we developed information needs for ecological, fate and transport, and human health indicators. By fate and transport, we refer to the pathways of radionuclides or contaminants from the source to the receptor (transport), and fate refers to the final concentrations of these contaminants in organisms (or tissues). While each section and the indicators listed may not be applicable to all current nuclear or hazardous waste sites, they will all be of concern in the siting of new nuclear facilities, whether they are on lands currently holding some nuclear plants or entirely new sites.

Information needs

Ecological concerns

Ecosystems are composed of the abiotic environment (rock and soil, water and air) and the biotic environment, including plants, animals, and microorganisms. All levels of biological organization (organisms, populations, communities, ecosystems, landscapes) are vulnerable to chemical/radiological, biological, and physical stressors. And while any disrupted environment faces physical and biological stresses, chemical and radiological contamination poses an additional problem for species because they have not evolved with these stressors.

Species or species assemblages, however, evolved with natural stressors and have mechanisms for adapting, although not necessarily to hazardous wastes. However, the mechanisms (e.g., intrinsic genetic variability, resiliency) that allow species to cope with natural stressors prepare them for adapting to anthropogenic stressors. There are three types of adaptation to disturbances or contamination: (1) adaptations of species through natural selection (a long process), (2) adaptation because of the plastic behavior of individuals, and (3) adaptations involving adjustments of assemblage structure and function. An example of plasticity of behavior would be animals whose food preferences are so broad that they can switch when one herb type, fruit, or prey is less abundant. In practical terms, this means that an animal is not restricted to only a few food items and is thus less vulnerable to population declines due to starvation. An example of plasticity would be a switch in prey type because preferred prey was eliminated. The ability of species to respond may preserve ecosystem health in the face of disturbances or changes in species composition or abundance due to chemical or radiological contamination. Thus, there is some natural recovery potential following any stressor or disaster. For example, the devastation caused by a lightning-initiated fire is similar to the effects of a human-caused fire; ecosystems can usually recover in both cases.

Regardless of whether an ecosystem is already degraded by the presence of hazardous waste (as might occur at USDOE sites or current nuclear power plants) or from potential disruption from sites under consideration for future power plants, ecosystems must be evaluated to assess potential exposures and effects. Here, we draw a distinction between ecosystem health and ecosystem integrity. Ecosystem health generally refers to the services it provides (clean air, water, species diversity), while ecosystem integrity refers to the possession of structure and function approximating an undisturbed ecosystem. Both can be endpoints of remediation, restoration following disturbances, and ecological evaluation for the siting of future nuclear facilities.

While many ecological assessments focus on two aspects (threatened and endangered species, goods, and services ecosystems provide), there are many other features that should be evaluated for a complete ecological characterization of a site. Information needs include characterization of aspects involving species, habitats, structure and function of communities and ecosystems, and landscapes (Table 1). Each level of organization must be evaluated because each is essential for understanding potential effects of operations and waste management from nuclear activities. It is easiest to assess species and habitat characteristics, but the overall structure and functioning of ecosystems must be assessed to determine long-term viability and sustainability. Without viability and sustainability, the ecosystem will not maintain its biodiversity or provide the goods and services, cultural, and aesthetic needs of different human communities, including Native Americans (Tano et al. 1996; Harris and Harper 2000; Burger et al. 2008).

Developing metrics for assessing the structure and functioning of ecosystems will become more important in the future as habitats become more limiting and isolated from other similar habitats (habitat fragmentation) (Sekercioglu and Sodhi 2007). It is in this context that landscape characterization assumes greater importance. Habitats on nuclear facilities (or proposed nuclear facilities) must be evaluated within the context of

Table 1 Key ecological information needed for evaluation of resources, which in turn can be used for making decisions about environmental management, restoration, and remediation, and for developing long-term stewardship plans for contaminated sites

Species and populations
Names of threatened/endangered species (both state/federal)
Names of unique assemblages (i.e. vernal pond amphibians, migrants)
Period of vulnerability (i.e. shorebird migrants in the fall)
Names of species of special concern (federal/state)
Species diversity of groups (i.e., 65 resident birds, 25 resident amphibians)
Lists of species groups of interest (i.e., neotropical migrants)
Changes in population sizes of threatened/endangered species
Changes in spatial distribution of species on site
Temporal trends and spatial patterns of abnormalities and deficits.
Importance of on-site species of concern to those off-site
Habitats
Description of habitats
Habitat diversity (number of different habitats, by acreage)
Unique habitats (i.e. pine barrens, shrub-steppe)
Habitats for endangered/threatened species
Proportion of different types of habitats
Proportion of natural habitat to industrial areas
Relationship of on- to off-site unique or rare habitats
Preserves on- and off-site
Degree of fragmentation of key habitats
Amount and dispersion of corridors connection habitats
Cultural, religious, and personal sites requiring intact ecosystems
Ecosystem structure
Relationship of different compartments
Physical structure of the plant environment (understory, canopy)
Soil and substrate characteristics
Relevant hydrology
Structure of the animal communities (number and ratios of prey, herbivores, predators, and decomposers)
Ecosystem functioning
Measures of productivity (i.e. biomass, or lumber logged)
Measures of nutrient flow and energy flow
Biochemical cycling
Delineation of types of functional ecoreceptors (food chain/trophic level analysis)
Number and extent of invasive species
Changes in numbers or distribution of endangered species
Spatial patterns of use of the site (by migrants)
Information on aquifers and watersheds
Food chain relationships
Predator/prey relationships and imbalances
Competitor relationships and implications
Landscape
Landscape matrix
Patch size and interspersion
Corridors for both terrestrial and aquatic systems
Refuges
Relative percentage of different habitat types
Build-out adjacent to site
Presence of protected ecological areas (preserves, parks)
Critical and unique habitats within and adjacent to site
Regional unique species, species groups, and habitats
Cultural or religious sites requiring intact habitats (Eco-cultural attributes)

This is not meant as an exhaustive list but as a starting point for site evaluation and management. The relative importance of each item depends upon the definition of the problem, and not all apply to every site (after Burger et al. 2004, 2007b; Burger 2007c, Unpubl. data) existing habitats in the region. On-site habitats that are not unique (i.e., with endangered or threatened species or species assemblages) but are becoming less common regionally assume a greater importance for protection. Landscape evaluation is often not required legally or by current regulations but should be given some priority because of changing landscapes and build-out in many regions.

The types of data needed for adequate characterization of species, habitats, structure, and function of communities, ecosystems, and landscapes are shown in Table 1. While several characteristics or parameters are listed for each level of biological organization, individual sites can select from this list, depending upon the ecosystems on site. For example, if there is a suite of endangered species or unique habitats on site, then the focus may be on these. However, some characteristics can be used across sites to understand status and trends, such as species diversity, habitat diversity, and proportion of the site that is industrialized land, biomass, and potential buildup. Others will be site-specific, depending upon the unique character of each site, including the presence of endangered, threatened, and special concern species.

Fate and transport

Conceptual Site Models that include possible sources and releases are important for understanding fate and transport (Mayer et al. 2005). Determining the sources and possible release sites is critical for radionuclides, particularly those with medium (decades) or very long (millennium) half-lives. Conceptual site models are often used to examine, clarify, document and communicate information about sources, transport and release sites, as well as routes of exposure and receptors (Mayer et al. 2005; Burger et al. 2006; ASTM 2003). To some extent, this is an integration task. For existing sites, the different sources, pathways, and plumes need to be integrated to predict future pathways of each different radionuclide or other contaminant separately. For new facilities, existing data should be used to predict these sources, release sites, and pathways.

If there has been adequate ecological characterization (see above, Table 1), then the question of potential ecological receptors has been delineated, and fate and transport questions mainly deal with sources and the transport pathways through ecosystems that should be adequately characterized (Table 2), although in reality, biota are important mechanisms of transport of chemicals and radionuclides. Fate and transport require the identification and examination of present contamination on site, whether from preexisting nuclear facilities or other on-site contamination. Current site conditions require data on contaminants (priority pollutants) in surface soil, subsoil, vadose, groundwater, presence of metals, PAHs, radionuclides, DNAPLs, and delineation of soil hotspots and plumes, often with careful sampling (see classic paper by Greenberg 1987).

Of special concern are the rapid exposure pathways (measured in meters per second or day) that might be present on, adjacent to, or near any facility, such as the presence of rivers, streams, or other corridors of contaminant transport, while underground plumes tend to move at a slow but inexorable pace (measured in centimeters per year). Most sites have a combination of rapid and slow transport pathways and the degree of biotic transport varies (see above).

While rapid exposure pathways are very important, understanding natural barriers and/or engineered containment structures must also be considered. Natural barriers include the characteristics of the particular environmental medium, such as sorption potential of subsurface materials for radionuclides, which could provide transport attenuation and decay before the radionuclides reach a potential human or environmental receptor. Engineered barriers include waste form alteration to reduce leaching potential and emplacement of materials to resist or remove rainwater that could infiltrate areas that have become contaminated or in which waste materials have been placed (Clarke et al. 2004; Chien et al. 2006; Leschine 2007; Trayham et al. 2008).

Human health

Human health information needs include both direct and indirect effects, the latter including

Table 2 Fate and transport information needs

Sources	
	Potential locations where releases or spills could occur
	Installation of detection systems in areas of higher probability for releases
	Avoidance of potential sources for which releases may not be detected in a timely manner e.g., underground tanks
	Presence of other nuclear facilities on site (size, extent)
	Presence and condition of spent nuclear fuel on site
	Storage Capacity for spent nuclear fuel on site
	Presence of other contaminant sources on site
	Levels of contaminants of concern on site
	Presence of other potential contaminant sources in the buffer itself or off site
Natural barriers	
	Presence of low hydraulic conductivity geological formations that would attenuate contaminant transport
	Presence of naturally occurring organic content that would retard contaminant transport through sorption processes
Surface water transport pathways	
	Rivers, streams or creeks on, adjacent to, or nearby to the site
	Presence of pools and lakes and their sediment systems
	Chemistry of waterbodies and sediments with regards to oxidation, reduction, sulfation, biomethylation and sequestration
	Corridors through habitats that allow rapid animal movement
	Topography and elevation gradients
	Prevailing winds or currents
Subsurface transport pathways	
	Soil and Geological pathways for plumes
	Physical properties of soil: porosity, hydraulic conductivity
	Chemical properties of soil: redox potential, anions and cations
	Biological properties of soil: organic compounds, burrowing animals
	Hydrology: is offsite surface and groundwater influenced by onsite water sources
	Aquifer characteristics, presence of aqufers, preferred pathways.

eco-cultural, aesthetic, and medicinal uses of ecological resources or sites (Table 3). Humans who may live, work, or play in proximity to a site will face aesthetic, practical, and health issues. Aesthetic issues involve perceptions of the neighborhood as well as visual features. Practical issues include changes in property values (down or up), transportation changes, and other neighborhood changes occasioned by introducing any large industrial facility. Health concerns over nuclear power have long been recognized as a risk perception challenge (Slovic 1987). The public has a high level of concern over nuclear accidents and nuclear contamination. Other exposure pathways include airborne emissions (on a regular basis) or accidental releases of radioactive gases (Slovic 1993; Kunreuther et al. 1990; Slovic et al. 1991; Mitchell 1992; Flynn et al. 1994). More likely, however, is the contamination of water sources used for drinking, gardening, or recreation. Understanding the specifics of public reaction or concern will allow these to be evaluated and may lead to modifications, reassurances, or incentives (Greenberg et al. 2007). A major difficulty arises when developers or regulators are at cross-purposes with the public, addressing issues that the public is less concerned about and ignoring those of higher concern (Hance et al. 1989).

The first consideration for a newly proposed site is to identify any current uses of the site (i.e., recreation) and the distribution of population around the site in terms of density in concentric circles or along transportation corridors. Topography plays an important role in the movement of contaminants, particularly surface contaminants from a site, as well as the distribution of airborne

Table 3 Human health information needs, including public health information needs of surrounding communities

Information systems
Information on knowledge, per eptions, concerns, and information needs
Information system in place for long term stewardship.
Timeliness and relevance of information
Degree of public/stakeholder input, acknowledgement and responses
Degree of integration of public/stakeholder concerns
Population characteristics
Percent residential, commercial, recreational
Density of each type
Spatial distribution of each type relative to the facility in concentric rings
Demographics
Ethnic composition
Vulnerable risk populations
Percent of children and elderly
Presence of daycare, schools, hospitals, senior facilities
Environmental data
Availability of surface and subsurface soil baseline contaminant data
Availability of groundwater contaminant data
Exposure pathways
Percent population use of well water and source (surface, ground)
Percent and extent of use of home gardens for food (types of plants)
Consumption of fish and game influenced by site
Exposure pathways for pets
Public health risk attributes
Site-specific information (history, alarm systems) available to public
Site specific information been made available to health providers and facilities (clinics, emergency centers, hospitals)
Extent of provision of potassium iodide (if so when, where, to whom, and how)
Number and type of access routes to nuclear facility
Number and type of access routes for surrounding communities
Percent of residences (families) with cars
Evacuation routes and capacity
Extent of catastrophic event planning

contamination from a source. Communities down wind or down slope of a site, or along waterways draining a site, will need special consideration. Although out of sight, the movement of contaminant plumes in the subsurface reaching homes or groundwater sources must be examined. The water sources utilized by nearby communities will be a major influence.

It is more difficult to predict future development and human habitation in proximity to new facilities, and guidance about controlling fence line development is currently lacking. Lessons learned from many cities that were industrialized early show the problems posed by a complex mosaic of industrial facilities closely surrounded by housing, dating from the time when people expected to walk to work.

Special issues for siting of nuclear facilities

The information needs discussed above are required for the siting of any new facility that might result in contamination of the environment, including nuclear facilities. However, there are two issues that relate directly to nuclear facilities and that provide some lessons learned; these will be discussed now.

Decommissioning and decontamination

DOE sites and other contaminated sites face a large task: decontamination and decommissioning of reactors and other facilities. This poses a unique challenge both for current facilities and for planning for future nuclear power plants.

While many nuclear power plants have received or applied for license extensions, they will eventually face decommissioning. The NRC has been quite active over the past few years in capturing lessons learned from decommissioning activities that have taken place, and these lessons learned should be incorporated into the design, siting, and construction of new nuclear facilities (www.nrc.gov/decommissioning). Examples include avoiding underground tanks and pools from which releases can occur undetected and avoiding the use of embedded piping. Even so, it is important for sites that are undergoing decommissioning to consider the checklists as well.

Temporal patterns

With nuclear plants, either governmental or commercial, understanding risk to humans and the environment in the broadest sense requires baseline information, information during construction and immediately following construction, and monitoring data thereafter. In many cases, especially in the aftermath of the finding of tritium in the groundwater at some reactor sites, commercial nuclear power plants have ongoing monitoring programs that can be implemented during construction of new facilities and thereafter. The nuclear industry should follow a three tiered approach: (1) prevent releases to the environment, (2) detect releases that do occur, and (3) manage those releases in a way that protects the environment. While the risks following construction may relate primarily to radiological and chemical contamination, the risk during construction often relate to physical disruptions, which result in ecological degradation. For example, building roads allows for the movement of invasive species into otherwise pristine ecosystems, and these invasive species may lead to declines in native species. Removal or disruption of soil can cause changes in the seed banks (thus, impacting the ecosystem that can develop on site). Changes in the water table as a result of road building or altering elevation gradients can completely change the ecosystem.

Integrating ecology, fate and transport, and human health characterization

Providing templates for data requirements to protect human health and the environment is timely, given that the USA is entering a new era of licensing nuclear power plants after a 30-year hiatus. The licensing process has been streamlined, mainly by providing four approved nuclear reactor designs. This has resulted in over 15 applications for nearly 30 new reactors (NRC 2008). Since the licensing process requires Environmental Impact Assessment, this paper provides lists of key variables in a framework that is useful for environmental assessments by petitioners, consultants, the NRC, and the public that want to make their own evaluations. The first step is to assemble all the available information sources (Table 4), to assemble a team able to address each of the main indicator categories (Table 5), and then to assemble, integrate, and synthesize the information provided in Tables 1, 2, and 3. Table 5 provides the overall framework and will be useful when discussing the importance of these sustainability indicators with public policy makers and the public.

Assessing the risk to humans and the environment for existing and new nuclear facilities requires developing information on three key aspects: ecology and environmental health, fate and transport, and human health. Ideally, acquisition of information about these three aspects will

Table 4 Risk assessment information needs for protection of current nuclear facilities and future sites

Availability and results of site-specific risk assessments (with citations)
Results of environmental impact statements
Results of comparisons with hazard quotients or benchmarks
Availability of screening risk values
Toxicity factors (by species, age class or other host factors)
Qualitative statements (i.e. woodpeckers appeared to decline)
Quantitative statements (i.e. woodpeckers declined by 80%)

The information needs apply to any facility with potential contamination

Table 5 Combining ecological, fate and transport, and human health information needs to provide a framework for the public and managers to make informed decisions about buffer zones needed for current nuclear facilities and the siting of new facilities

Ecological
Species, populations, communities, ecosystems, and landscapes
Structure and functioning of ecosystems
Habitats and biomes
Threatened and endangered species and habitats
Unique assemblages or unusual phenomena
Fate and transport
Sources
Natural barriers
Surface water transport pathways
Subsurface transport pathways
Human health
Information systems
Population characteristics
Vulnerable risk populations
Environmental data
Exposure pathways
Public health risk attributes
Risk assessment
Ecological risk
Human health risk
Risk balancing
Selection of appropriate endpoints, indicators, sentinels, surrogates
Risk management
Relationship of assessments to remediation options
Relationship of assessments for buffer lands to protect humans and the environment
Linking risk assessments to laws and regulations
Developing decision matrices for actions

Partly derived from Tables 1, 2, 3, and 4. These are the basic concepts needed to select new sites for nuclear power plants, to evaluate current plants, and to make remediation decisions for nuclear facilities (after Burger et al. 2004, this ms)

occur simultaneously, with integration and collaboration among the areas. Further, the indicators selected for each of the three will be interrelated, provide information for the others, and will together form a more coherent package than each alone. Although the information can be assembled by specialists in each field (ecology, environmental health, fate and transport engineers), it clearly needs to be integrated among all three during all phases of the evaluation of sites for current or new nuclear facilities.

Conclusions

As USA moves toward diversification of energy production, nuclear energy will become more important, and public opposition to nuclear power may be declining (Greenberg et al. 2007; Whitfield et al. 2008; Nuclear News 2009). Although no new nuclear plants were licensed in the US for over 30 years and the last plant completion was in 1995, there are now over 15 applications for nearly 30 reactors, mainly on existing sites (NRC 2008). In the intervening decades, universities and the government have lost some of the trained personnel and experience necessary to conduct risk evaluations to protect human and the environment as they relate to siting of nuclear power plants. In this paper, we propose a set of items or variables that should be examined by contractors, regulators, NRC personnel, policy makers, and the general public. Not all items will apply to all sites, but these lists will be useful for consistency among and within sites.

Further, and perhaps more importantly, new nuclear facilities are being established monthly in China and other developing countries, and new plants are being built in many countries throughout the world. The issue of monitoring and assessing the buffer zones around such facilities will gain in importance as more facilities are constructed, particularly in areas that are heavily used for agriculture or residences.

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