Paper

APPLICATION OF AN INFORMATICS-BASED DECISION-MAKING FRAMEWORK AND PROCESS TO THE ASSESSMENT OF RADIATION SAFETY IN NANOTECHNOLOGY

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Abstract—**The National Council on Radiation Protection and Measurements (NCRP) established NCRP Scientific Committee 2-6 to develop a report on the current state of knowledge and guidance for radiation safety programs involved with nanotechnology. Nanotechnology is the understanding and control of matter at the nanoscale, at dimensions between ~1 and 100 nm, where unique phenomena enable novel applications. While the full report is in preparation, this paper presents and applies an informatics-based decision-making framework and process through which the radiation protection community can anticipate that nano-enabled applications, processes, nanomaterials, and nanoparticles are likely to become present or are already present in radiation-related activities; recognize specific situations where environmental and worker safety, health, well-being, and productivity may be affected by nano-related activities; evaluate how radiation protection practices may need to be altered to improve protection; control information, interpretations, assumptions, and conclusions to implement scientifically sound decisions and actions; and confirm that desired protection outcomes have been achieved. This generally applicable framework and supporting process can be continuously applied to achieve health and safety at the convergence of nanotechnology and radiation-related activities.**
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INTRODUCTION

The National Council on Radiation Protection and Measurements (NCRP) established NCRP Scientific Committee 2-6 to develop a report on the current state of knowledge and guidance for radiation safety programs involved with nanotechnology. Nanotechnology is the understanding and control of matter at the nanoscale, at dimensions between ~1 and 100 nm, where unique phenomena enable novel applications (NNI 2012). As illustrated in Fig. 1, the context of this work is at the nexus of safety, health, well-being, and productivity; risk management; and an emerging technology. The effort supports the premise for radiation protection in the 21st century that guidance should keep in step with the changing times, including the changes and development of new technologies in medicine, in industry, and for societal uses (Boice 2014). The intent of the report is to provide operational information of practical value to radiation safety officers, operational health physicists, dosimetrists, workers, management, and regulators.

THE CONVERGENCE OF NANOTECHNOLOGY AND RADIATION-RELATED ACTIVITIES

As stated by the National Nanotechnology Initiative (NNI 2012), the full definition of nanotechnology includes all three of the following features:

- research and technology development at the atomic, molecular, or macromolecular levels, in the length scale of ~1–100 nm;
- creating and using structures, devices, and systems that have novel properties and functions because of their small and/or intermediate size; and
- ability to control or manipulate on the atomic scale.

As illustrated in Fig. 2, particles in the nano-size range occur in nature or can be “engineered.”

Nano-sized particles present in ambient air that are not deliberately manufactured are primarily produced by

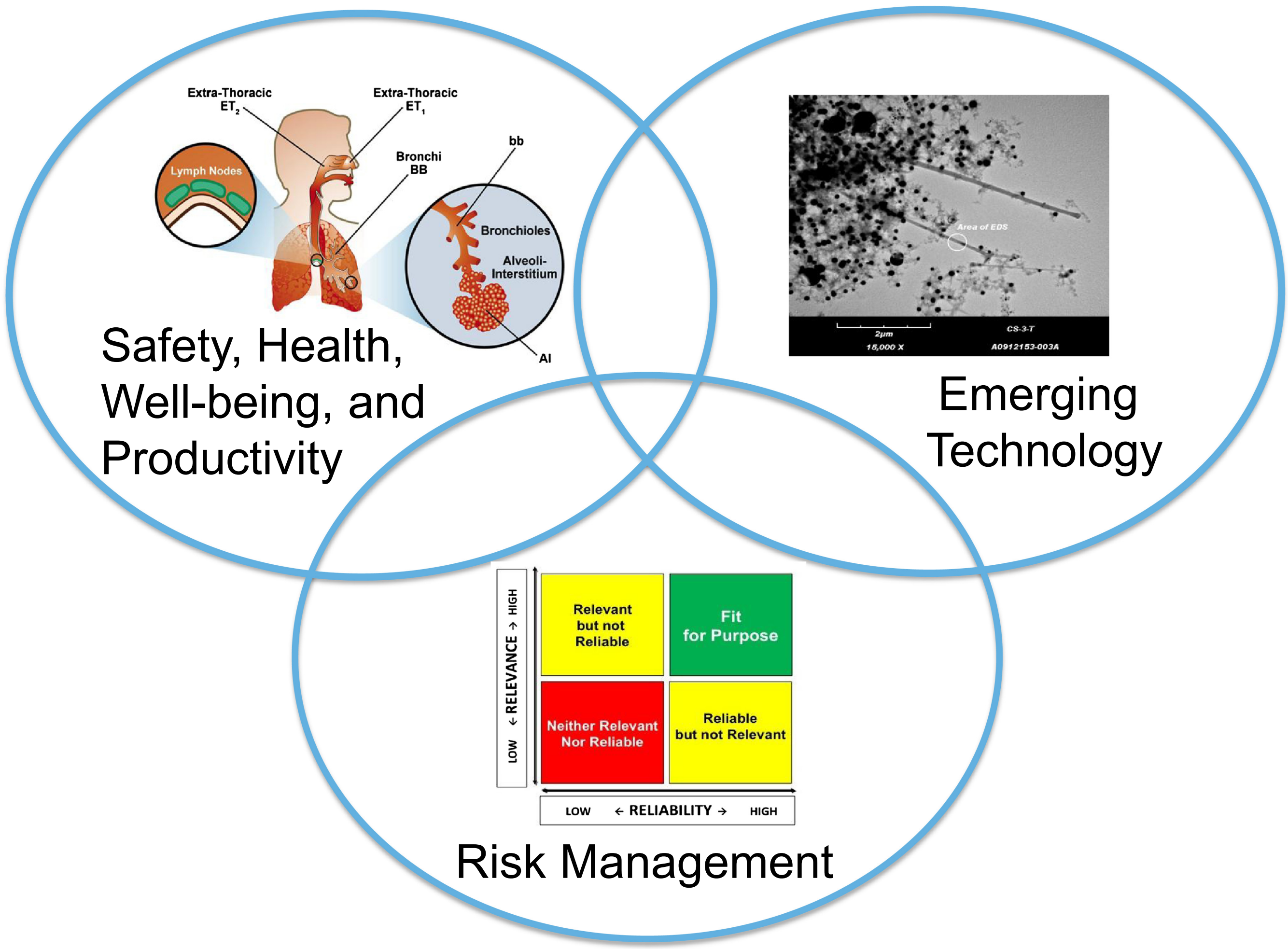

Fig. 1. Context of the current work (adapted from Cash 2014).

combustion processes (e.g., domestic solid-fuel heating and cooking) and have both man-made (e.g., vehicle emissions, industry) and natural (e.g., forest fires, volcanic action, ocean spray) sources. The radioactive decay of radon gas to atoms of solid elements results in nanoparticles containing polonium, bismuth, and lead.

As illustrated in Table 1, the convergence of nanotechnology and radiation-related activities can be characterized in a number of ways, ranging from definitions of the activities, types of applications, and common and differing aspects of the historical radiation safety and industrial hygiene health and safety protection practices.

As noted in the table, in recent years, a number of manmade nanoparticles, including those that are radioactive, have been developed and incorporated into a wide variety of engineered materials (e.g., Chanda et al. 2010a and b; Sheets and Wang 2011; Simonelli et al. 2011; Zyklotron 2012). Applications are being found in a broad range of medical, industrial, educational, and consumer products; their use is rapidly expanding. In some cases, radiation is being used to create or alter materials at the nanoscale (IAEA 2005). Nanoengineered structural materials, metals, coatings, coolants, ceramics, sorbents, and sensors may be particularly useful in radiation-related applications (TMS 2012).

Areas of interest include programs where radiation or radioactivity are being used to characterize or alter materials at the nanoscale, to radiolabel nanomaterials for tracking or evaluation of physicochemical and biological behavior, or to use nano-formulated materials in situations involving radiation or radioactivity. Knowledge gaps regarding information to implement appropriate radiation safety programs in these settings are being identified. Questions of interest include how traditional health physics program practices may need to be modified to provide adequate safety for working with radioactive nanomaterials or working with radiation in nanotechnology applications. Some guidance on exposure assessment considerations for nanoparticles in the workplace, including radioactive nanoparticles, has been provided (e.g., Hoover et al. 2007; Hoover 2011a). Issues related to nanotechnology and the law have also been addressed (e.g., Feitshans 2012).

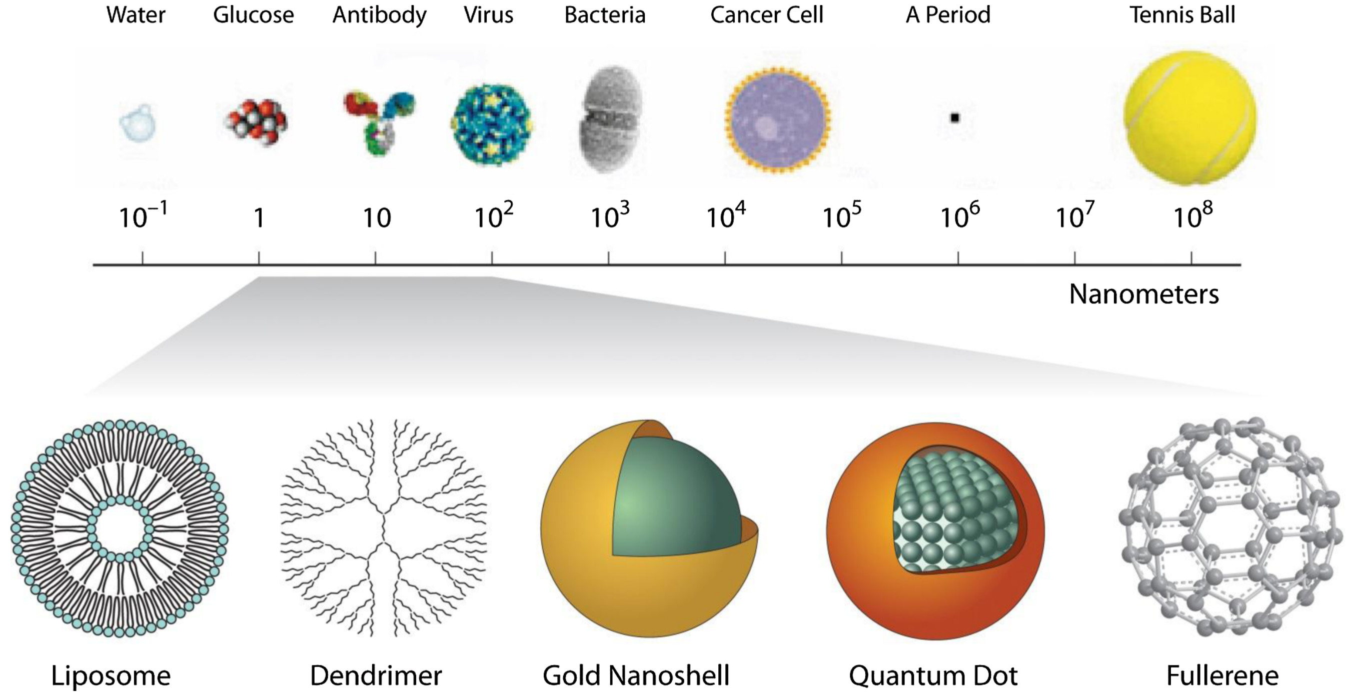

Fig. 2. Illustration of the relative size of objects including nanomaterials (McNeil 2005).

The areas of risk perception and risk communication can be problematic for both nanotechnology and radiation-related activities. Kahan (2009) has noted that public perceptions of the risks of nanotechnology are evolving. Kahan and Rejeski (2009) have presented a comprehensive strategy for nanotechnology risk communication, which involves aspects of message framing, credibility, and the recognition that the best scientific evidence will not necessarily permeate public opinion and policy making automatically. As noted by Boice (2014), "Without sound communication of content, skilled communicators of message, and effective outreach to the proper audiences (policy setters, members of the public, patients, and professionals), the message perishes. We [the radiation protection community] must do better." Locke (2011) has summarized lessons learned from discussions at the 2010 NCRP annual meeting on the communication of radiation benefits and risks in decision-making. Lessons incorporate interactive communication, including social media, to put risks into context and to empower stakeholders. Boice (2014) has further noted that, in recognition of the importance of communication, the NCRP Board of Directors has approved the creation of the new NCRP Program Area Committee 7 on Radiation Education, Risk Communication, Outreach, and Policy.

AN INFORMATICS-BASED DECISION-MAKING FRAMEWORK AND PROCESS

While the full report is in preparation, this paper describes and applies an informatics-based decision-making framework and an associated ongoing process within that framework for success in proactive understanding and management of potential hazards, exposures, and resulting risks at the confluence of nanotechnology and radiation-related activities. The premise is that use of a robust framework and process is essential to successful answering of complex questions. As noted by risk-management expert Ed Zebrosky (1991): "The method is not the message; [the message] is in the managerial frame of mind determined to make robust decisions."

Many of the details presented here about the framework and process have been drawn directly from a recent chapter on confirming critical terminology concepts and context for clear communication (Hoover et al. 2014) published in the *Encyclopedia of Toxicology* (Wexler 2014). As noted in that chapter, the framework and supporting process were developed to be generally applicable to meeting any objective. As described in this current paper, they can be applied continuously to achieve radiation safety in nanotechnology as well as safe nanotechnology in radiation-related settings.

The informatics aspect of the approach is based on the following working definition expanded from the *Nanoinformatics 2020 Roadmap* (de la Iglesia et al. 2011): Nanoinformatics is the science and practice of determining which information is relevant to meeting the objectives of the nanoscale science and engineering community; developing and implementing effective mechanisms for collecting, validating, storing, sharing, analyzing, modeling, and applying the information; confirming that appropriate decisions

Table 1. Considerations at the convergence of nanotechnology and radiation-related activities.

	Nanotechnology	Radiation-related activities
General description	Nanotechnology is the understanding and control of matter at the nanoscale, at dimensions between ~1 and 100 nm, where unique phenomena enable novel applications.	Radiation-related activities include power production, medical diagnosis and treatment, nuclear weapons, and a wide range of industrial applications.
Examples of convergence	• Radiation-based nano-synthesis methods	• Nano-enabled materials such as carbon nanotubes for components, piping, structures, and enhanced concretes
	• Annealing processes	• Noble-metal enrichment using palladium for self-healing of cracks
	• Characterization tools	• Coatings, barriers, and coolants
	• Aging studies	• In-core reactor applications
	• Special systems such as plasma-focus-based radiation sources	• Physical, chemical, and radiological separations and sorbents
		• Sensors and security applications
Hierarchy of control for managing hazards, exposures, and risks	• Elimination • Substitution or modification • Engineering controls • Warnings and administrative controls • Personal protective equipment	
Understanding of health effects	Health consequences of exposure to nanomaterials are the subject of current research.	Health consequences of exposure to radiation have been extensively studied.
Guiding risk management approach	Historical industrial hygiene practice uses occupational exposure limits (OELs) based on concerns for a variety of health-related effects and endpoints. Few OELs have been developed for nanomaterials. "Control banding" of nanomaterials and work tasks is promising.	Historical radiation protection practice involves OELs for exposures to radiation and radioactive materials that are based on the unifying concept of radiation dose; *such a unifying concept is not available for assessment of health risks from exposure to nonradioactive materials.*
Risk perceptions	Perceptions of the potential health and environmental risks of nanotechnologies are evolving.	Perceptions of risks from the uses and exposures to radiation are generally negative.
Risk communication	Research on what types of risk communication strategies are necessary is ongoing. Message framing and contextualization are important.	There is an urgent need to do better, including rebuilding trust, and developing improved communication plans, materials, and outreach.

were made and that desired mission outcomes were achieved as a result of that information; and finally conveying experience to the broader community, contributing to generalized knowledge, and updating standards and training. Successful missions apply all of the steps in the process.

The ARECC decision-making framework

The decision-making framework of *anticipate, recognize, evaluate, control, and confirm* (ARECC) illustrated in Fig. 3 arises from the field of industrial hygiene (i.e., Brandt 2010; Hoover et al. 2011) and supports hazard-, exposure-, and risk-informed decision making in any endeavor. The framework began as *recognize, evaluate, and control*; was strengthened to *anticipate, recognize, evaluate, and control* in 1994, when then-president of the American Industrial Hygiene Association (AIHA) Harry Ettinger added the anticipate step to formally encourage the worker protection community to proactively apply its growing body of knowledge and experience; and the framework was expanded to ARECC (Hoover et al. 2011) to confirm that all steps in the decision-making framework were being effectively applied and that the desired outcomes were being achieved. Overall confirmation of the adequacy of decision making for risk management can include evaluation of results from occupational epidemiological studies. Confirmation of training, documentation, and continuous improvement of the entire decision-making process can ensure that all steps are scientifically grounded and appropriately applied.

Application of ARECC in the current context is intended to enable the radiation protection and nanotechnology communities to:

- *anticipate* that myriad nano-enabled applications, processes, nanomaterials, and nanoparticles are already present or may become present in radiation-related activities;
- *recognize* specific situations where environmental and worker safety, health, well-being, and productivity may be affected;

Fig. 3. A robust decision-making framework for proactive understanding and management of hazards, exposures, and resulting potential risks to safety, health, well-being, and productivity through application of a science- and practice-based approach to building and sustaining leaders, cultures, and systems that are relevant and reliable and over which we have influence (Hoover et al. 2011, 2014).

- *evaluate* how radiation protection practices may need to be altered to improve protection;
- *control* information, assumptions, interpretations, and conclusions to implement scientifically sound decisions and actions; and
- *confirm* that desired protection outcomes have been achieved.

The framework recognizes the essential contributions of leaders, cultures, and systems to achieving success. The long history of radiation protection has fostered senior-management support and leadership of radiation protection programs, a strong safety culture, and the development and use of well-documented and proven procedures. When failures have occurred, root causes of those failures can be traced to shortcomings or breakdowns in one or more aspects of the prevailing leaders, cultures, and systems. Note that the ARECC elements of training, documentation, and improvement shown in Fig. 3 support the premise that relevant and reliable leaders, cultures, and systems must be built and sustained. In addition, inclusion of the caveat "over which we have influence" recognizes that relevant and reliable leaders, cultures, and systems can only exist to the extent that they can be influenced. Aspects of the decision-making framework and process related to building and sustaining relevant and reliable leaders, cultures, and systems can be particularly important when disparate technologies or activities are converging.

As described further in the following sections, the supporting elements of the process include:

- communication and education message and audience-planning matrix for meaningful exchange of information with relevant stakeholders (Table 2);
- CLEAR-communication assessment criteria for use by both readers and communicators of nanotechnology, radiation protection, and risk-related issues (Fig. 4);
- example flaws in decision making (Fig. 5);
- five quadrant tools to assign relevance-versus-reliability, align know-versus-show, adapt to temporal-versus-spatial variability, interpret model-versus-measurement certainty, and refine perception-versus-reality aspects of information (Fig. 6); and
- four proactive steps to engage the community, inform the interested, reward the responsive, and understand and incentivize the reluctant to foster community support and involvement (Fig. 7).

Table 2. A communication and education message and audience-planning matrix of general applicability (Hoover et al. 2014).

	Workers	Health and safety practitioners	Managers	Policy makers and regulators	Equipment and facility providers	Materials suppliers	Financiers	Insurers	Legal community	Researchers	Educators	Students	Emergency Responders	Media	Consumers	Society
Literacy and Critical Thinking Skills																
Real Life Examples																
Understanding (not rote application)																
Continuous Improvement																
Modeling and Sharing																
Assessment																

Specific messaging and actions in each element of the matrix must be based on (a) what knowledge and understanding each stakeholder needs and (b) what knowledge and understanding each stakeholder can provide.

As noted in the Encyclopedia chapter, use of the framework and approach as described here is not intended to preclude the use of other frameworks and processes that may be useful as well.

A communication and education message and audience-planning matrix

The communication and education message and audience-planning matrix illustrated in Table 2 can be used in conjunction with the ARECC decision-making framework to identify, build, and sustain relevant and reliable leaders, cultures, and systems within key stakeholder groups.

The communication and education process can be tailored by the stakeholder group to understand their roles, responsibilities, needs, and potential contributions, and to engage their collaboration. In the case at hand, this applies for knowledge relevant to both radiation safety in nanotechnology as well as to safe nanotechnology in radiation-related settings.

The example stakeholder list originated from the point of view of advancing occupational safety, health, well-being, and productivity in any context. The list begins with workers, because all individuals are workers to some extent. Frequently overlooked subgroups in the workplace include maintenance, custodial, security, contractor, and volunteer workers, as well as visitors. The list extends through health and safety practitioners; managers; policy makers and regulators; equipment and facility providers; materials suppliers; financiers, insurers, and the legal community; researchers; educators; students; emergency responders; the media; consumers; and society in general. The list can be expanded or contracted and serves to incorporate relationships of safety, health, well-being, and productivity from the earliest steps of planning, design, and outset of any activity, facility, or system, rather than as an afterthought.

Most individuals fall into more than one category, with needs and abilities to obtain or provide information that may be similar or different from those of other stakeholders. For example, health researchers who also serve as health and safety practitioners must ensure their own protection as well as protection of their students and colleagues in a research setting. The information needed to identify, plan, fund, and conduct their work safely may be the same or different from that needed to inform a vendor of their equipment and system needs, obtain study materials from qualified suppliers, or educate their target audiences about the results. Effective communication is essential to ensuring that nanotechnology and radiation-related activities do not converge unexpectedly in operations in any way that might change the durability, reactivity, functionality, or any other aspect of a material or operation that could be relevant to safety, health, well-being, and productivity.

The communication and education attributes in the row aspect of the planning matrix were adapted from the American Statistical Association *Guidelines for Assessment and Instruction in Statistics Education (GAISE) Report* (Franklin et al. 2007). They are:

1. emphasize literacy and build, sustain, and apply critical thinking skills;
2. develop and use real-life data examples;
3. stress conceptual understanding rather than mere application of procedures;
4. foster continuous improvement and active discussions;
5. use technology for developing conceptual understanding and for analyzing and sharing information (e.g., modeling and simulation, databases, wikis, etc.); and
6. use assessments to evaluate and improve the efficacy and impact of these activities.

Stakeholder-specific communication and education for each element of the matrix requires dialogue among the stakeholders and tailoring of message development based on (a) what knowledge and insights each stakeholder needs and (b) what knowledge and insights each stakeholder possesses and can provide.

A set of CLEAR communication assessment criteria

Fig. 4 uses the word CLEAR as an acronym to convey a set of five assessment criteria (concise, logical, ethical, accurate, and relevant) that flow "from the ground up" in a pyramid configuration to help readers and writers ARECC effective communication in general, and as described here, to understand and manage issues of radiation safety for nanotechnology in particular. The details of the CLEAR communication assessment criteria were originally developed to guide a formal scientific review process for physicians and other healthcare professionals (Iskander 2012). A variety of word choices were considered for the anagram, and the choice of individual words and their meanings in the

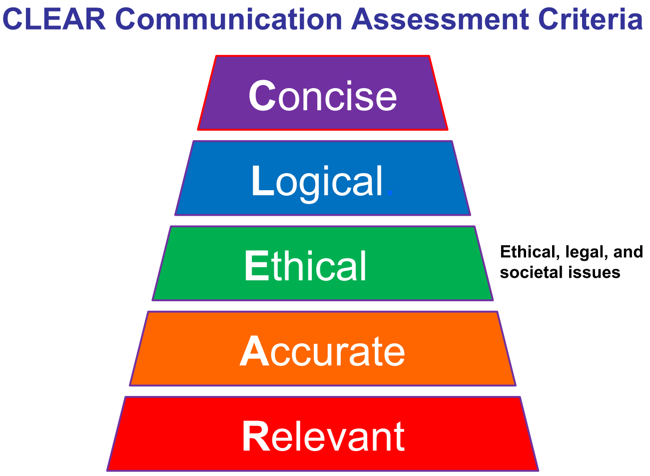

Fig. 4. A set of CLEAR communication assessment criteria for use by writers, reviewers, and practitioners (Hoover et al. 2014).

Fig. 4 acronym can be adjusted to support the needs and concerns of any reader, writer, reviewer, or practitioner.

Relevant to the reader and writer missions and needs is the foundational criterion for CLEAR communication. Readers must assess and ensure that the content of the presentation is relevant to the details of their situation (e.g., type and form of hazard and nature and magnitude of exposure), including issues of any potential bias or conflicting or competing interests on the part of the writer. Similarly, writers need to assess and ensure that their products are fundamentally relevant to their mission and expertise and tailored to the needs of their intended audience.

Accurate is shorthand for matching the certainty of presentation to the reliability of supporting information. For issues that are not yet well understood, an introductory informational pamphlet or web posting might highlight a growing issue of concern without implying more than is justified by the current state of knowledge. For issues that have been extensively studied and understood according to rigorous scientific procedures, the degree of certainty in the presentation might be justifiably higher.

Ethical is shorthand for ensuring that all ethical, legal, and social implications of the work are on a solid footing. By its very nature, work in the realm of health and safety must not only be conducted in a manner that is thoroughly ethical and legal, but it must be readily apparent that such is the case. *Informed consent* is a well-recognized tenet of research ethics.

Logical is shorthand for ensuring that the intended message is organized and conveyed in a manner that is not only scientifically and technically defensible but also fundamentally understandable. Logic can extend to issues of plain language and use of language that is tailored to the intended audience.

Concise, the crowning criterion, does not necessarily mean "short" but focuses on ensuring that any extraneous materials are rejected or moved to other communications so that the core message of the communication can be readily understood and applied. Note that application of the concise criterion supports the creation of comprehensive resources such as encyclopedias, which are not short but whose individual components are designed to address and meet specific reader needs. In the case of radiation safety and nanotechnology, an informatics goal is to identify and assemble a useable body of knowledge from authoritative sources such as NCRP, the National Institute for Occupational Safety and Health (e.g., NIOSH 2011, 2013), the International Atomic Energy Agency, the International Commission on Radiological Protection (ICRP), and AIHA (e.g., Gao et al. 2014; Hoover and Rickabaugh 2014). Additional resources include the GoodNanoGuide (https://nanohub.org/groups/gng); the National Nanotechnology Initiative signature initiative on Nanotechnology Knowledge Infrastructure—Enabling National Leadership in Sustainable Design; and the signature initiative on Nanotechnology for Sensors and Sensors for Nanotechnology, "Improving and Protecting Health, Safety, and the Environment" (http://www.nano.gov/signatureinitiatives); the Nanomaterial Registry (https://www.nanomaterialregistry.org); the AIHA Nanotechnology Working Group (https://www.aiha.org/get-involved/VolunteerGroups/Pages/Nanotechnology-Working-Group.aspx); and the Nanotechnology Committee of the Health Physics Society (http://hps.org/aboutthesociety/organization/committees/committee66.html).

Example flaws in decision-making

Fig. 5 lists a number of flaws that can affect the quality of CLEAR communication and associated decision making.

Information customers, creators, curators, and analysts can be aware of these potential flaws in decision-making. At the 00 Level, before any other actions are taken, the most fundamental flaw is lack of CLEAR objectives, based on the communication assessment criteria described above. In situations such as applications of radiation in nanotechnology or applications of nanotechnology in radiation-related activities, objectives might include protection of workers, protection of the environment, assurance of product or process quality, preparation for emergencies, or demonstration of compliance according to regulatory or other requirements. Attention to avoiding flaws in the setting of CLEAR objectives is followed at the Flaw 0 Level by failure to address uncertainty, which affects all aspects of study design and conduct. Flaws 1 and 2 correspond to the essential and widely recognized Type 1 and Type 2 statistical errors (jumping to a false-positive conclusion or making a false-negative conclusion).

Example Flaws in Decision-Making

Type	Attribute
00	Lack of CLEAR objectives
0	Failure to address uncertainty
1	False positive conclusion
2	False negative conclusion
3	Inappropriate decision level
4	Inappropriate evaluation method
5	Equating correlation and causation
6	Inappropriate extrapolation
7	Inadequate documentation
8	Mishap or misconduct

Fig. 5. Example flaws in decision making (Hoover et al. 2014).

Flaw 3 is using an inappropriate decision level, such as planning an action that has a 5% chance of failure (1 in 20 events) when a failure rate of less than 1 in 1,000 is needed to protect involved individuals. Flaw 4 is using an inappropriate evaluation method, such as only testing the toxicity of a substance by ingestion when the actual route of administration includes inhalation. Flaw 5 is equating correlation with causation, such as when the mode of toxic action may be associated with a contaminant in a test material rather than with the substance thought to have been tested. Flaw 6 is inappropriate extrapolation of information to a situation for which the test conditions are irrelevant, unreliable, or both. Flaw 7 is inadequate documentation, which can be particularly important in legal or regulatory settings. Flaw 8 addresses the reality that experiments, data, or information can sometimes be inadvertently miscollected or misrecorded or that someone may deliberately falsify results.

Relevance-versus-reliability assignment

Fig. 6a (the first of the suite of five quadrant tools) presents a triage process for readers to assign information according to its relevance and reliability for a specific application.

Information assigned to the "fit-for-purpose" category can be given priority for interpretation and action. Not all information is fit-for-purpose. Information developed for ecotoxicology may be highly relevant and sufficiently reliable for its intended use but irrelevant to questions in human toxicology. Some information may appear to address a relevant question but may only be of a preliminary nature and, therefore, unreliable. The details are important. As new work is proposed, writers and researchers can use the relevance-versus-reliability assignment process to guide fit-for-purpose development of new information.

Know-versus-show alignment

Fig. 6b presents a complementary process for aligning a need/ability to know something versus the need/ability to show it. Risk management expert Stan Kaplan (1991) has noted that, "If money is being spent to reduce an already minuscule risk while larger risks are going unaddressed, that is not only foolish; it is in effect an unsafe act." Thus, the know-versus-show process addresses the importance of the intelligent allocation of resources to understand and document risk-related information.

It would be ideal if all information RELEVANT to a concern could be both known and shown. Additionally, it would be ideal to clearly establish what information falls into the "know but not show" or "neither know nor show"

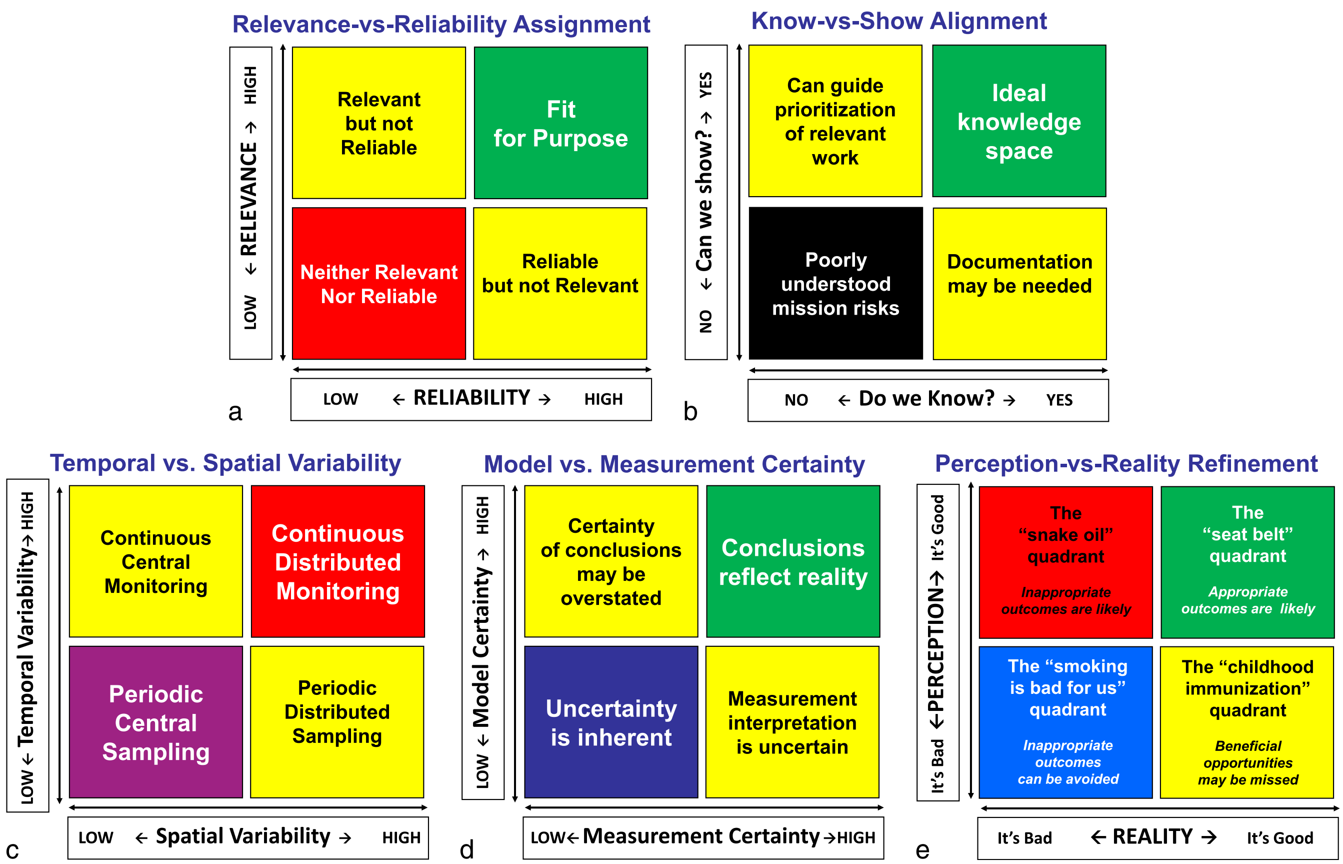

Fig. 6. Suite of five quadrant tools to (a) assign relevance-versus-reliability, (b) align know-versus-show, (c) adapt to temporal-versus-spatial variability, (d) interpret model-versus-measurement certainty, and (e) refine perception-versus-reality aspects of information (panels a, b, and e are adapted from Hoover et al. 2014).

categories. Medical studies conducted according to good laboratory practice rightly require extensive documentation such as checklists, signatures, photography, etc., to "show" what was done. Knowing what others have done can avoid duplication of work. Thus, establishing what is in the "it can be shown that this is not known" category has value for guiding the prioritization of relevant work. Better sharing of nanotechnology-related information can make efforts to improve safety, health, well-being, and productivity more efficient and effective. Knowing and being able to show through measurements and defensible documentation that an action or condition is present does not necessarily mean that an appropriate interpretation or response to that action or condition is available or even possible.

Temporal-versus-spatial variability

Fig. 6c (a new addition to the original suite of quadrant tools presented in the Encyclopedia chapter) addresses the need to adapt the frequencies and locations of hazard and exposure assessments to the temporal and spatial variability of activities in the workplace or environment. Situations can range from periodic central sampling to continuous distributed monitoring. Periodic confirmatory measurements are allowed in radiation protection situations that are relatively constant with time and location (i.e., NRC 2013). Continuous monitoring may be needed if conditions vary or have significant potential to vary.

Model-versus-measurement certainty

Fig. 6d (also a new addition to the suite of quadrant tools) addresses relationships among the certainty of a measurement (such as determination of the airborne particle size distribution of a radioactive nanomaterial), the certainty of the model in which the measurement is used (such as a workplace or atmospheric dispersion model, a model of deposition in the respiratory tract, or a model of potential health effects), and the certainty of associated conclusions. Using measurements of low certainty in models that require input data of high certainty can result in overstating the certainty of conclusion. Investing in collection of high certainty measurements when only models of limited certainty are available can result in conclusions that are less reliable than may ultimately be possible. Intelligent decisions require investment in the development of both defensible measurements and defensible models to interpret those measurements. At any time in the risk assessment process for any activity, the certainty of conclusions should be appropriately established.

Perception-versus-reality refinement

Fig. 6e illustrates the need to refine perceptions when the perception of what is bad or good, toxic or nontoxic, safe or unsafe does not match reality.

When perception matches reality, then engaging in actions associated with what is referred to here as the "seat belt" quadrant makes it more likely that good outcomes will occur. Similarly, avoiding actions associated with the so-called "smoking is bad for us" quadrant enables bad outcomes to be avoided.

Informed action may be needed to refine perceptions in a manner that moves misperceived situations out of the "snake-oil" quadrant (where inappropriate outcomes are likely because a bad action is perceived to be good) and out of the "childhood immunization" quadrant (where beneficial opportunities may be missed because a good action is perceived to be bad).

In addition, correctly perceiving an action as being good or bad does not ensure the action is appropriately engaged in or avoided. For example, seat belts are good for us, and we generally perceive them to be good for us, but some still do not use seat belts. Similarly, smoking is bad for us, and we generally perceive smoking to be bad for us, but some still smoke. Thus, our ability to advance safety, health, well-being, and productivity depends on our ability to understand and refine the match between perception and reality and ultimately to improve appropriate compliance. Given that nanotechnology is an emerging technology, there are perception questions about the inherent safety of nanomaterials and their applications, and mismatches of perception and reality have long plagued fields involving radiation and radioactive materials.

Four steps to a total culture of safety, health, well-being, and productivity

To build on individual efforts by readers, writers, reviewers, and practitioners, it makes sense to view clear communication as a community effort involving everyone who may be concerned about or able to take action to create a favorable outcome for an issue. As illustrated in Fig. 7, fostering community understanding and application of the decision-making framework to build and sustain a total culture of safety, health, well-being, and productivity requires a community effort through the following four steps:

1. engage the community;
2. inform the interested;
3. reward the responsive; and
4. understand and incentivize the reluctant.

The work of NCRP to develop the report on radiation safety aspects of nanotechnology is evidence of a commitment to engaging the community to improve safety, health, well-being, and productivity, especially through ensuring radiation safety in nanotechnology and safe applications of nanotechnology in radiation-related settings. The interest of the radiation protection community in becoming informed about sound decision-making approaches in this area will be evident through the reading of this paper and engagement in an ongoing process to develop, share, and

Fig. 7. Four steps for community action (Hoover et al. 2014).

apply meaningful information and guidance. It is hoped that readers and those with whom they partner will be rewarded by success in building and sustaining collective safety, health, well-being, and productivity. An organized message and audience-planning matrix such as described above can increase the likelihood of successful communication. Such an approach, in conjunction with criteria for assessing communications, can be especially valuable in encounters with stakeholders who may be reluctant to engage in the process.

EXAMPLE ASSESSMENTS AT THE CONVERGENCE OF NANOTECHNOLOGY AND RADIATION-RELATED ACTIVITIES

The following sections present examples of how the convergence of nanotechnology and radiation-related technologies can be assessed. The examples involve aspects of airborne particle behavior; collection efficiency for nanoparticles by filtration; implications for deposition in the human respiratory tract, including the relationships among physical, thermodynamic, and aerodynamic diameter; and particle-size associated aspects of radiation dosimetry.

Example of particle behavior considerations for filtration and respiratory protection

To the extent possible given the current level of understanding, guidance needs to be provided on contamination control; engineered and administrative controls; and personal protective equipment, including respiratory protection, training, waste disposal, and emergency response. The particle-size dependence of filtration efficiency and of the deposition location of particles in the human respiratory tract are examples of the types of issues that pose special concerns for nanoparticles. As shown in Fig. 8, mechanisms influencing particle motion and collection on surfaces including the respiratory tract include gravitational sedimentation, inertia, interception, Brownian diffusion, electrostatic attraction, and thermal diffusion. Knowledge of the particle size distribution is needed to estimate the dominant mechanisms of motion that will govern particle behavior in general and deposition mechanism in particular.

It is generally recommended that high-efficiency particulate air (HEPA) filters be used to clean exhaust air from containment systems and facilities where radioactive materials in a dispersible, or potentially dispersible, form are used (NCRP 1998). A standard definition of a HEPA filter is one for which aerosol filtration efficiency is greater than or equal to 99.97 % for particles of 0.3 μm, diameter (USDOE 2005). High efficiency filters generally are defined in relation to particles of around 300 nm, as this is typically regarded as the most penetrating particle size (MPPS). Theoretical models of filtration (e.g., classical single fiber theory) predict the highest filtration efficiencies for particles <20 nm, where diffusion deposition dominates, and >1 μm in diameter, where sedimentation and inertia dominate, with the minimum filtration efficiency for particles around a few hundred nanometers in diameter (Hinds 1999). These theoretical predictions are confirmed by experimental studies (Kim et al. 2007; Wang 2013). Thus, HEPA filters should be effective for the filtration of airborne nanomaterials (NIOSH 2009). It is important to note, however, that the value of the MPPS can be significantly reduced to <100 nm by electrostatic effects in some filter media (such as those typically used in respiratory protection) that are treated to have enhanced collection of particles by electrostatic forces, compared to values of the MPPS that are >100 nm for "mechanical" filters (Rengasamy et al. 2008, 2013; Hinds 1999).

Fig. 9 illustrates how these mechanisms of particle collection are reflected in the actual penetration results for a common filter medium with a collection efficiency greater than 95% used for respiratory protection.

As shown in the example in Fig. 9, the MPPS for this electrostatically enhanced filter occurs in the size-range of ~30 nm where there are minimal Brownian diffusion and inertial effects. As expected, for particles smaller than the MPPS, the rate of penetration of particles decreases rapidly because very small particles are effectively collected as a result of Brownian diffusion. As expected, penetration also decreases for particles with diameters greater than the MPPS because larger particles are effectively collected by inertial impaction. Information about the expected aerosol size distribution in a given situation can be compared to the expected filtration efficiency to determine the expected overall efficiency of particle collection. Particles smaller than or greater than the MPPS will be of lesser concern than particles of size at or near the most penetrating size.

As illustrated in Fig. 10, similar to the collection behavior of particles in filter media, the particle size of airborne material determines its deposition site within the human respiratory tract. For workplace exposures, in the absence of specific information about the physical characteristics of the aerosol to which a subject is exposed,

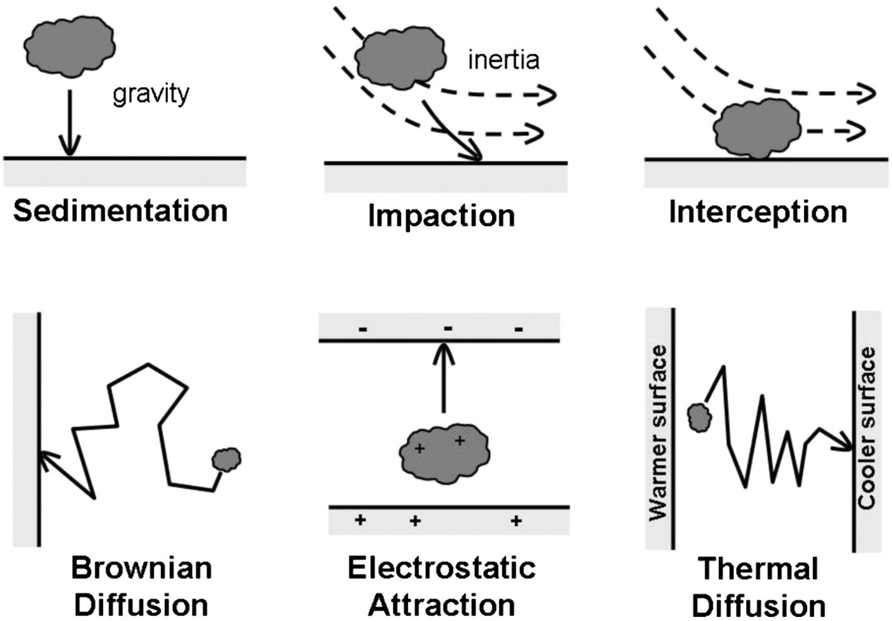

Fig. 8. Fundamental mechanisms of particle collection in the environment, in air filtration and air cleaning systems, and in the human respiratory tract (Hoover 2011b).

Section 5.8.1 of ICRP (1994) recommends a default value of 5 μm activity median aerodynamic diameter (AMAD) with geometric standard deviation = 2.5, particle density = 3 g cm^{-3}, and particle shape factor = 1.5. For indoor or outdoor exposures of members of the general public, the recommended default value is 1 μm AMAD with geometric standard deviation = 2.47, particle density = 3 g cm^{-3}, and particle shape factor = 1.5. The value of 3.0 g cm^{-3} for density is recommended because it is typical of many natural materials.

Note that the alveolar deposition fraction for 5 μm aerodynamic diameter particles (the workplace default assumption diameter) is lower than for 1 μm (the environmental default assumption diameter), which is lower than for 0.1 μm (upper end of the nano-size range), which is lower than for 0.015 μm (corresponding to the highest alveolar deposition for the conditions modeled in this example). Thus, knowledge of particle size will be important for effectively understanding and managing inhalation exposure risks in activities involving radiation and nanotechnology.

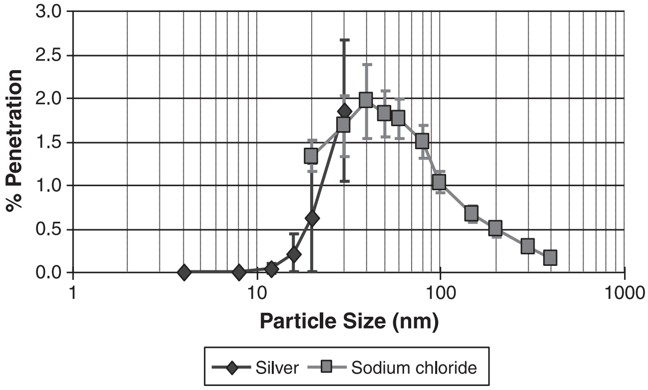

Fig. 9. Example of data collected using a combination of test aerosols to determine the MPPS and penetration percent for an electrostatically enhanced filtering-facepiece respirator with overall collection efficiency greater than 95%. Each data point represents the mean and standard deviation from the evaluation of five samples of the respirator (Rengasamy et al. 2008).

Examples of the relationship among particle volume equivalent diameter, thermodynamic diameter, and aerodynamic equivalent diameter

The complete understanding and interpretation of particle size includes the relationships among particle physical diameter (which can be expressed as particle volume equivalent diameter d_e), particle thermodynamic diameter d_{th} (which

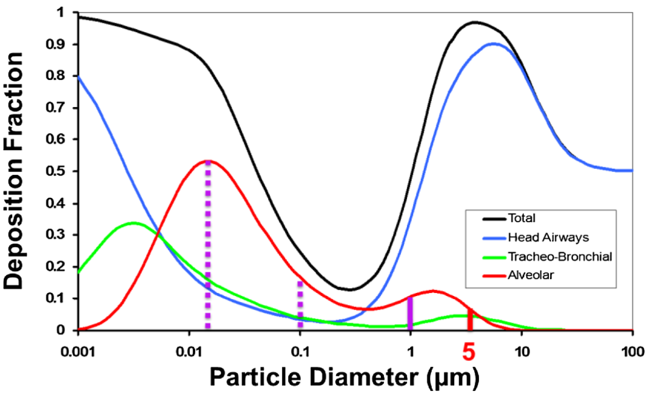

Fig. 10. Illustration of the particle size dependence of deposition in the human respiratory tract as calculated for spheres of unit density from the ICRP Publication 66 Human Respiratory Tract Model for an adult male, light exercise, nose breathing (adapted from ICRP 1994).

characterizes the diffusion-dominated behavior of a particle), and particle aerodynamic diameter d_{ae} (which characterizes the gravitational and inertial behaviors of a particle). ICRP (1994) equates particle volume equivalent diameter d_e with particle thermodynamic diameter d_{th} and provides the following relationship in Section D.4.1 of Annex D of ICRP Publication 66 to translate back and forth as necessary between d_{th} and d_{ae}:

$$d_{ae}=d_{th}\frac{\rho C(d_{th})}{\chi \rho_0 C(d_{ae})},$$

where ρ_0 is the default value of unit density (1 g cm^{-3}), ρ is the actual density of the particle, χ is the shape factor of the particle (which ranges from one for a sphere to two for a plate-like particle), $C(d_{th})$ is the Cunningham slip correction factor for a particle of thermodynamic diameter d_{th}, and $C(d_{ae})$ is the Cunningham slip correction factor for a particle of aerodynamic equivalent diameter d_{ae}. The Cunningham slip correction factor accounts for the fact that the ability of particles to "slip" between air molecules is affected by the relationship between their physical diameter and the mean free path of the air though which they are moving (i.e., the mean distance traveled between air-molecule collisions). For air at a temperature of 25 °C and a pressure of 760 mm Hg, the mean free path is 0.067 μm (i.e., in the nano-size range). Note that as particle density increases, the value of d_{ae} increases. In other words, denser particles are aerodynamically larger. Note that as the value of the shape factor increases, the value of d_{ae} decreases. In other words, elongated or plate-like particles behave as if they are smaller than spherical particles of equivalent volume. This will be the case for fiber-shaped nanomaterials such as carbon nanotubes.

The enabling feature of having a system that involves both d_{th} and d_{ae} is that particles of any size, shape, and density can be described by their characteristic thermodynamic or aerodynamic behavior. For example, in the case of a dense radioactive material, assuming that the density of the airborne particles is 10 g cm^{-3} and that the particles are round, smooth spheres with a shape factor of one, then a particle with a volume equivalent diameter of 1 nm will have d_{th} = 1 nm and d_{ae} = 10 nm (taking into account the fact that the values of the Cunningham slip correction factors are 237 for a particle of 1 nm diameter and only 25 for a particle of 10 nm diameter). Similarly, a spherical particle of density 10 with a volume equivalent diameter of ~50 nm will have d_{th} = 50 nm and d_{ae} = 285 nm.

As shown in Fig. 11, particle deposition in the respiratory tract is the same, regardless of which type of diameter is used. In the upper plot involving thermodynamic diameter, the deposition fraction for a 1 nm diameter particle is essentially 100%. Moving to the lower plot, if the particle has density of 10 g cm^{-3} and shape factor one (i.e., d_{ae} = 10 nm), then the deposition fraction is, of course, once again essentially 100%.

Similar, equivalent results can be seen for the d_{th} = 50 nm and d_{ae} = 285 nm example, as well as for particles of any other size, as long as there is sufficient knowledge of (1) the volume equivalent diameter, (2) the shape factor, and (3) the density.

As illustrated in the upper plot, deposition as a function of thermodynamic diameter does not require knowledge of particle density for particles smaller than about 30 nm thermodynamic diameter. However, knowledge of density becomes critical for particles of larger size. For example, for a particle of thermodynamic diameter of 30 nm, deposition is only about 10% for a particle of density 1 g cm^{-3} but is nearly 70% for a particle of density of 10 g cm^{-3}.

Similarly, as illustrated in the lower plot, deposition as a function of aerodynamic diameter does not require knowledge of particle density for particles larger than about 1 μm aerodynamic diameter, but knowledge of density becomes critical for particles of smaller size. For example, for a particle of aerodynamic diameter 30 nm, deposition is only about 10% for a particle of density 1 g cm^{-3} but is nearly 50% for a particle of density of 10 g cm^{-3}. Thus, knowledge of particle density will be important for effectively understanding and managing inhalation exposure risks in activities involving radiation and nanotechnology, especially for airborne particles for which density is difficult to determine, such as those comprising loosely formed aggregates or agglomerates of individual nanoparticles or nanofibers.

Example assessment of information on the biokinetic behavior of nano-PuO_2

Specific guidance is needed for conducting internal dosimetry programs if radioactive nanomaterials are being handled. Possible differences in the biological uptake and in vivo dissolution or translocation of radioactive nanoparticles, compared to more commonly encountered μm-sized particles, may impact the design and conduct of dosimetry programs. In particular, as noted in the particle behavior example above, how nanosized particles are addressed in current respiratory tract and systemic dosimetry models can be evaluated. Model parameters and considerations, including deposition efficiency, total and regional retention patterns, and cells and tissues at risk; dose calculation methods; and the potential for multifactorial biological effects from radiation, chemical, and physical particle properties of the nanoparticles, also need to be considered.

As an example of how such examinations might be done, Cash (2014) recently addressed the issues of risk-informed decision making for potential inhalation of

^{239}Pu and ^{238}Pu dioxide nanoparticles. The risk-informed approach reflected guidance developed by the National Academies/National Research Council (NA/NRC 2009). Given the lack of human data, biokinetic behavior of nanoplutonium particles was derived from animal experiments. Data from the Smith et al. (1977) and Stradling et al. (1978) studies in rats were relevant. In those studies, ^{239}Pu and ^{238}Pu particles were size-fractionated by filtration. Smith et al. reported a uniform physical size of 1 nm for particles in their <25 nm size fraction and a mass median physical diameter of 48 nm for material in their 25–220 nm size fraction. Animal exposure was by injection and pulmonary intubation, so the studies did not directly assess delivery of particles to the respiratory tract by inhalation, and results from instillation studies might not be the same as for delivery of particles to the respiratory tract by inhalation. Animals were serially sacrificed for analysis of plutonium distribution in organs, tissues, urine and feces.

As shown in Fig. 12, Cash (2014) used data from these studies to describe the relationships between lung burden and amount of radioactivity in urine and between estimated radiation dose and amount of radioactivity in urine. The validity of the relationships shown in the figure are based

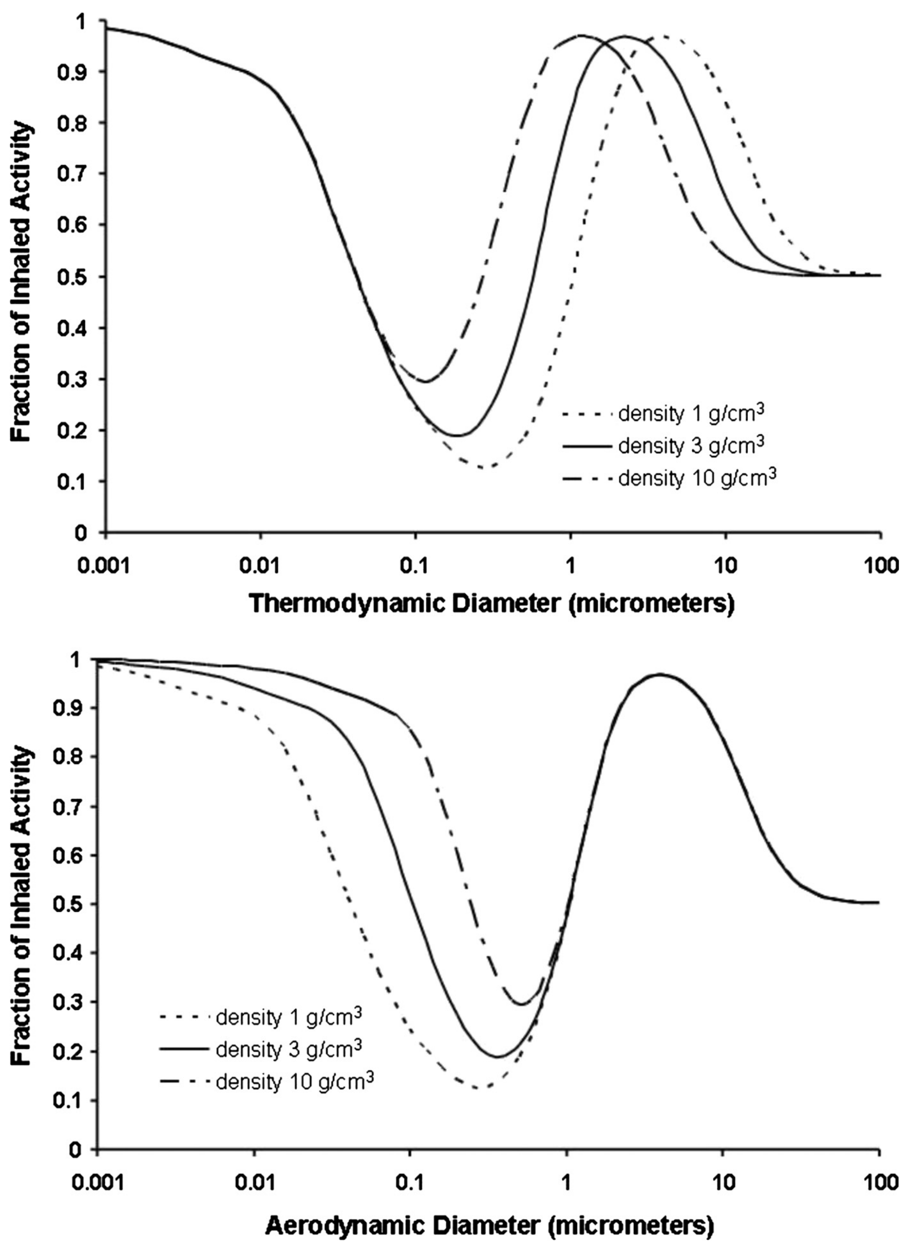

Fig. 11. Comparison of total deposition fraction in the human respiratory tract as a function of (above) thermodynamic diameter and (below) aerodynamic diameter [adapted from ICRP (1994) and Hoover (2011b)].

on the assumption that the biokinetic behavior of plutonium observed in the rat injection and instillation studies can be applied to the human inhalation exposure situation.

Examination of the modeling results shown in Fig. 12 reveals differences in how bioassay measurements of the amount of plutonium in urine as a function of time after exposure can be interpreted as estimates of the initial amount of inhaled activity (left curve) and estimates of radiation dose (right curve). As shown in Fig. 12, using information on the biokinetic behavior of nano-plutonium in the rat studies suggests higher urinary excretion of nano-^{239}Pu compared to excretion based on the default particle size assumption the ICRP Human Respiratory Tract Model (ICRP 1994) that the inhaled plutonium dioxide had 5 μm AMAD with a geometric standard deviation of 2.5. For example, assuming that the PuO_2 was inhaled as particles with the ICRP default workplace particle size of 5 μm AMAD would mean that the observation of a daily urinary excretion rate of 1 Bq plutonium for an individual at 10 d after occurrence of the inhalation exposure would indicate that the fraction of initially inhaled plutonium was 2×10^{-7} Bq and that the initially inhaled amount was therefore 2×10^{7} Bq. However, if the material was actually inhaled as particles with 1 nm activity median thermodynamic diameter (AMTD), then the fraction of initially inhaled plutonium would actually be 1×10^{-4}, and the initially inhaled amount would therefore be only 1×10^{4} Bq.

Similarly, as shown in Fig. 12, use of the biokinetic data from the available animal studies predicts that the committed effective dose per unit measured activity in urine is higher for the larger default-sized particles. For example, if the observed daily excretion rate is 1 Bq plutonium for an individual at 10 d after the inhalation, then an assumption that exposure was to particles with 5 μm AMAD would indicate a committed effective dose of 30 Sv, whereas the actual dose would be only 2 Sv if the inhaled particles were 1 nm AMTD in size. Thus, to the extent that the biokinetic data from the animal studies is predictive of the behavior of nano-plutonium in humans, bioassay interpretation based on use of that data in conjunction with assumption of an exposure to an aerosol with the default particle size may be conservative. However, as with any effort to use data from animal studies to assess behavior of a material in humans, the interpretation may or may not be conservative for other physicochemical forms of plutonium or other radionuclides. As noted by Cash, the evaluation of laboratory animal data illustrated how material-specific biokinetic information might be used to adjust the HRTM model assumptions about particle solubility and size and thereby obtain a more representative interpretation of bioassay measurements. This ^{239}Pu example involved using a greater degree of solubility than the default materials and a smaller particle size than the default size. It is prudent to keep in mind that Cash's work and associated conclusions are based on a single set of experiments in which plutonium was produced using one method (i.e., exploding foil). There are other studies (e.g., Kanapilly and Diel 1980) where plutonium nanoparticles were very insoluble, to the point where the Cash conclusions might be reversed. When possible, developing material-specific information can improve the assignment of radiation dose and justify expenditures on controls or limitations on exposures. This is an example of insights that should help in the development of informed guidance for risk assessment and management of potential exposures to nano-formulated radioactive materials.

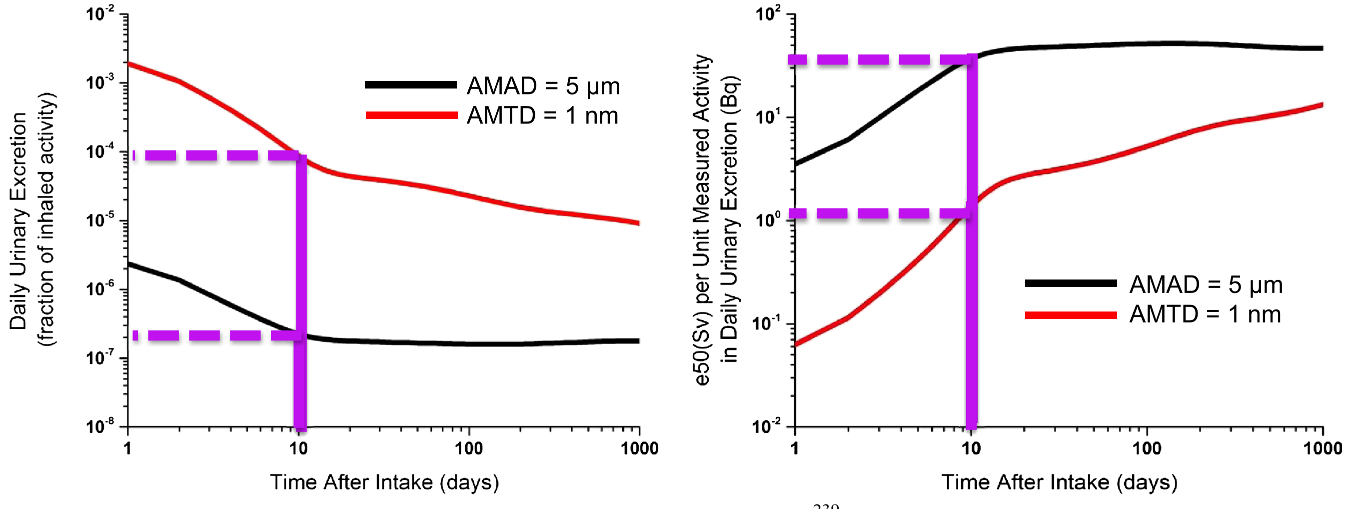

Fig. 12. Illustration of bioassay interpretation for humans exposed by inhalation to ^{239}Pu particles of 1 nm activity median thermodynamic diameter compared to particles of the ICRP default workplace aerosol size assumption of 5 μm activity median aerodynamic diameter, assuming that biokinetic information obtained from rat injection and instillation studies is relevant to the human inhalation exposure situation (adapted from Cash 2014).

CONCLUSION

While the full NCRP report on radiation safety aspects of nanotechnology is in preparation, the intent of this paper has been to illustrate a framework and process for addressing the convergence of radiation safety and nanotechnology and to provide examples of important issues of science and practice at that convergence. The ARECC decision-making framework; the communication and education message and audience planning matrix; the CLEAR communication assessment criteria; the example flaws in decision making; the relevance-versus-reliability, know-versus-show, temporal-versus-spatial, model-versus-measurement, and perception-versus-reality quadrant tools; and the four steps to a total culture of safety, health, well-being, and productivity are examples of how we might effectively assess, understand, communicate, and apply critical concepts and context. Success is more likely if leaders, cultures, and systems are proactively built and sustained to understand and manage hazards, exposures, and resulting potential risks at the convergence of nanotechnology and radiation-related activities. As noted in the frame-of-mind quote from Zebroski (1991), robust risk management begins with a determined commitment by all stakeholders to rigorous decision-making processes. Considerations described above are being taken into account as the report on radiation safety aspects of nanotechnology is being developed, and these considerations for a robust decision-making framework and process can be applied continuously to build and sustain leaders, cultures, and systems for safety at the convergence of nanotechnology and radiation-related activities.

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