CONSTRUCTING A RESEARCH AND DEVELOPMENT FRAMEWORK FOR INTEGRATING NANOTECHNOLOGIES WITH NUCLEAR TECHNOLOGIES

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Authorization to Submit

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Abstract

In the last two decades, nano scale chemistry and physics have delivered a profusion of extraordinary results not achievable by conventional means. In the same time frame, the early promise of nuclear science has weathered numerous setbacks, many of which were the result of reliance on conventional materials and methods subjected to extraordinary circumstances. Curiously, these two extremely sophisticated fields of technical endeavor have not been broadly examined in conjunction despite the well documented needs of nuclear science for better methods and materials. Leaving the question, how could an effort to explore the intersection of nanotechnology and nuclear challenges be structured and managed?

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Chapter 1: Overview

1.1 Introduction

In the last two decades, nano scale chemistry and physics have delivered a profusion of extraordinary results not achievable by conventional means. In the same time frame, the early promise of nuclear science has weathered numerous setbacks, many of which were the result of reliance on conventional materials and methods subjected to extraordinary circumstances. Curiously, these two extremely sophisticated fields of technical endeavor have not yet been broadly examined in conjunction despite the well documented needs of nuclear sciences for better methods and materials and the well documented superior characteristics of nano methods and materials.

In the fall of 2010, I assisted in organizing and conducting the first of a series of workshops involving nuclear and nano scientists from National Laboratories and industry. This Lockheed Martin sponsored workshop ignited interest among the participants and served as a stepping stone for the next two workshops. The February 2012 Nuclear Fuels & Materials NanoNuclear workshop was jointly hosted by the U.S. Department of Energy, Nuclear Energy Program (DOE-NE) and Rice University's Richard E. Smalley Institute of Nanoscience and Technology, Houston Texas. The final workshop in this series was jointly hosted by DOE-NE and The Minerals, Metals, & Materials Society and held in Gaithersburg Maryland, June 2012. Over the course of these three workshops, it became apparent that: 1) nanotechnology has significant potential for addressing long-standing nuclear challenges and 2) the limited research in nanonuclear that is being conducted has no central focus, no established forum for information exchange, and no coherent set of objectives (Winston & Marshall, 2012) (Collaborative report on the workshop, 2012).

The primary purpose of this thesis is to examine the potential of forming a linked framework for exploring the intersections of nano science and nuclear technology. This will be set against the current backdrop of fragmented, isolated pockets of research with, as yet, few meaningful applications. Leaving the question,

how could an effort to explore the intersection of nanotechnology and nuclear challenges be structured and managed?

Please note, for brevity and convenience, herein I frequently use the word "nano" to describe the whole field of nano sciences and nanotechnology and "nuclear" to describe the gamut of nuclear technologies and sciences.

1.2 Scope of Study

The current situation is not a case of "solutions looking for problems". Nano already has prolific applications in adjacent highly technical fields. Nuclear has real technical problems and a wide expanse of divergent public opinions and perceptions.

The scope of this thesis effort is limited to examining the potential for nano-enhancements in each of the following categories:

- Physical properties
- Mechanical properties
- Chemical properties
- Thermal properties
- Separations processes
- Fabrication processes
- Management of radioactive wastes.

Though societal and political aspects affecting public policy regarding nuclear and nano are important considerations, they are beyond the scope of this inquiry.

1.3 Research Method

The research method was a situational analysis to gauge relative value that nanonuclear research might yield. "Situational analyses seek to analyze a particular situation of interest through the specification, re-representation, and subsequent examination of the most salient elements in that situation and their relations" (Clarke, 2005). Potential value was assessed with respect to a current baseline constructed from available literature. "Value" in the context of this assessment relied on possibilities suggested by gains resultant in comparable, adjacent applications of nanotechnology to issues and problems in nuclear technology applications.

It was recognized that such "gains" necessarily had to be calibrated against specific problems and that adaptation to the attendant purpose could be accompanied by unique risks previously not encountered. Attempts to estimate the likelihood of such risks and possible consequences would have compounded conjecture with speculation. Rather than over-extend what is already a largely hypothetical exercise, the study was limited to recognizing and acknowledging the need to address risks by applying carefully tempered precautionary principles.

Performance was evaluated in engineering and economic context although it is recognized that society as whole frequently applies subjective measures as well.

Because technology revolutions hinge as much on chance as on deliberate design, today's cutting edge is often tomorrow's obsolete. The trajectory of nuclear technology could abruptly change. Accordingly, this study looked at both the current challenges in nuclear science and the most likely alternative nuclear technologies that may emerge in the future.

The approach I followed was to cross the major issues in nuclear power against the related nanotechnology applications in other fields. I first created plausible constructs in which nano advances in other fields

might yield benefit to specific nuclear challenges. Then these constructs were vetted with subject matter experts in each specific area to validate assumptions and framing of the issue. These constructs formed the bases for discussions with nanotechnology experts in the immediately relevant and potentially applicable disciplines.

1.4 Data Collection

Federal funding levels for both nano and nuclear research were compiled and contrasted. This information served to provide a notional backdrop for examining the differences in how these fields are regarded and how that translates into the political support necessary to instigate and sustain appropriations. Two categories of relevant information were considered: research expenditures in nano and nuclear separately versus expenditures on nanonuclear per se and physical/chemical attributes of conventional materials and methods used in the nuclear industry versus comparable attributes of nanomaterials.

A situational analysis from available literature was conducted to evaluate the presumption that the remarkable attributes of nano materials and nano methods can be meaningfully translated to address nuclear challenges. This was done by taking a specific nuclear research initiative and searching for separate, but closely similar nano research efforts.

Interviews were conducted with the following subject matter experts:

- Nano experts not currently engaged in applying their work to nuclear challenges,
- Nano experts who are actively engaged in nanonuclear research,
- Nuclear researchers' who are currently involved in nanonuclear research,
- Nuclear researchers' not currently employing nanotechnology.

These discussions were structured to ensure that each respondent was given an opportunity to provide input on the same topics as the others. See appendix A for an Interview Question/Answer Matrix.

The explanatory information provided herein is taken from notes I compiled while participating in the seminars preceding the nanonuclear workshops and while conducting interviews with experts. To the extent that I was able to fully comprehend the more technical aspects of each, I attempted to validate concepts using information obtained on the internet and by submitting drafts to those I interviewed to correct.

Because all of the experts I interviewed had participated in one or more of the previous nanonuclear workshops, the sample cohort is clearly biased toward those favoring expanded research in this area. I attempted to counterbalance this by including skeptical assessments from available literature.

1.5 Current Baseline

As of 2014 there are 430 operating nuclear power plants around the world, a few dozen large research reactors and 240 small research reactors, and in excess of 30,000 cyclotrons producing radioisotopes worldwide for scientific and medical purposes ("Nuclear Power in the World Today", 2014) (Michigan State University, 2007).

Public perceptions of nuclear power are mixed tending toward negative (recent attitudes are more favorable) while nuclear medicine is widely regarded as essential and viewed positively (Nuclear Energy Institute, 2014) (Polls and Publications, 2011). Scientific research in nuclear technology doesn't register much reaction either way. The general public is largely oblivious to industrial uses of radioactive materials.

The US Department of Energy funding for various nuclear research and technology development amounted to $21.086 billion in FY2014. Of that, roughly $488 million was directed to applied nuclear energy research and combined nuclear research programs. Environmental cleanup of radioactive and mixed waste comprised of roughly $5 billion of the total DOE nuclear expenditures ("Budget of the U.S. Government: Appendix" , 2014).

DOE-funded nano research amounted to $396.59 million from 2006 to 2014. For the same period, the National Nanotechnology Initiative (NNI) was funded by various federal agencies at $1.7 billion (which includes the forementioned funding from DOE)(National Nanotechnology Initiative, 2014).

Chapter 2: Nanotechnology

2.1 Nanotechnology

In the late twentieth century, tools such as the Scanning Tunneling Microscope (STM) enabled observation of phenomena occurring at the scale of one billionth of a meter (Binning & Rohrer, n.d.). With those tools, scientists in virtually every discipline began exploring ways to purposefully manipulate materials at that scale and from that emerged what has come to be known as "nanotechnology". It should be recognized that some of the capabilities now classified under this term have been in practice for a very long time, in the case of certain ceramics, for thousands of years ("Nanotechnology has a rich history," n.d.) Even the process of making nuclear fuel, which extends back more than 60 years, requires grinding a powder to less than 100 nanometers in size before sintering (Nuclear Fuel Process, 2014). But until there was a means to directly observe structures at this scale, understanding of what was happening and what was being made was difficult, sometimes agonizingly slow, and often ambiguous. Thus, like the explosion of our knowledge of the universe that the telescope made possible, the rapid expansion of methods and materials at the nano scale as well as the accompanying broad notoriety of the associated term, was enabled by a few fundamental, but quite sophisticated, types of looking glasses.

While the label "nanotechnology" is a convenient means of describing the sciences of the very small, it can also be misleading, suggesting that there is a singular, all-encompassing discipline that it represents. Such is not the case. Nanotechnology includes biological systems, mechanical systems, organic chemistry, inorganic chemistry, metallurgy, physics, electronics, thermodynamics, and virtually every other field of science and engineering ever contemplated or practiced. Consequently, each field of endeavor is populated with its own specialized nano methods and means unique to the application/purpose and the list of these grows almost exponentially with each passing day as more and more experimenters avail themselves to the burgeoning potential.

Graphene and other carbon allotropes dominate general awareness of nanotechnology at both the lay and technical level, but they comprise only one corner of this domain. Although carbon nanomaterials were among the first to be categorized as such, this continuing primary association may be due to their extraordinary mechanical properties , high electrical and thermal conductivity, transparency to visible light, and high specific area (Li, et al., 2010, pp. 4328-4334)(Bolotin, et al., 2008, pp. 351-355)(Stoller, et al., 2008)(Lee, et al., 2008, pp. 385-388)(Balandin, 2011, pp. 569-581).

Manipulation of these properties via chemical functionalization/surface modification is an expanding area of material sciences that potentially extends to making components for nuclear applications. This includes high-quality graphene materials and composites in structures such as metal-organic frameworks, polymers, and inorganic nanostructures (Barron, personal communication, 2014).

While there are literally thousands of variations of the basic methods employed to make or manipulate different nanomaterials, most are derived in one way or another from chemical vapor deposition, exfoliation, expitaxial growth, intercalation, or ablation. At the most fundamental level, some of these methods are so simple that they can be easily performed almost anywhere. Exfoliation is simply peeling a single atomic layer off of a surface and can be done with scotch tape, in fact the 2010 Nobel Prize in Chemistry was awarded to two scientists who studied graphene production by literally employing this as a starting point.

Epitaxial growth is a method of growing single crystals on a substrate under a high vacuum and was invented at Bell Laboratories in the 1960s for making electronics (Morton Jr. & Gabriel, 2007). Chemical vapor deposition is exactly what it sounds like—the condensation of a vapor layer onto a specific substrate at a carefully controlled rate under rigorously controlled conditions (Park & Sudarshan, 2001).

Among the most immediately useful materials from an engineering perspective are the composites that can be formed by combinations of nanomaterials. The composites formed using layers or "lamellae" (successive "plates" bonded one on top of the next) are known as lamellar structures. There are two different

types of lamellar nano-composites: intercalated and exfoliated. The intercalated nano-composites are constructed from polymer chains alternating with a specific number of inorganic layers. Exfoliated nano-composites have a randomly variable number of polymer chains between the layers and the layers stand about a nanometer apart. Because of the fixed ratio between the polymer layers, intercalated nano-composites have very specific electronic and thermal transport properties. Exfoliated nano-composites have superior mechanical properties (Prasad, et al., 2006, pp.654-659).

Intercalation is a hybrid that combines distinctly dissimilar nanomaterials in ingenious ways to make new novel composites with extraordinary properties beyond those of the "parent" nanomaterial. It encompasses a large variety of composites including one-dimensional, two-dimensional, three-dimensional and amorphous materials, made of components mixed at the nanometer scale. Typically these are formed by interleaving organic and inorganic layers or fibers of "parent" materials to make new materials with specifically targeted physical or chemical properties.

The types of inorganic components used range from three-dimensional framework systems such as zeolites to two-dimensional layered materials such as, clays, metal oxides, metal phosphates, chalcogenides (compounds based on one or more of the chalcogens, oxygen, sulfur, selenium, tellurium, or polonium), and even single molecule monomers (sometimes referred to as one-dimensional and zero-dimensional materials) such as (Mo3Se3) chains and clusters (Kickelbick, 2007). The organic components are generally carbon in the form of graphene, carbon nanotubes, fullerenes, nanodiamonds, or other carbon allotropes.
Some of the chemicals and methods used for bulk synthesis of graphene are extremely toxic and volatile posing hazards to the persons preparing the material and potentially representing risks to the environment. Consequently, as the demand for high purity graphene continues to grow, research on production methods has expanded to electric arc, plasma, microwave, and laser assisted approaches (Tour & Winston, personal communication, 2014).

Graphene is but one of literally thousands of nanomaterials now produced in bulk. Nanostructures of

uranium have been made by Notre Dame in 2010 (Sigmon, et al., 2010, pp. 13395-13402). Burgett and his team at Idaho State University have made single crystals of uranium oxide (Andrei, 2013). Boron nitride nanotubes and nanosheets are being examined in multiple applications including lightweight shielding for protecting radiation sensitive componentry on satellites (Fay, et al., 2012). Niobium carbide has been tested by Barron and colleagues as a coating for turbine blades for hypersonic jet engines.

Chapter 3: Nuclear Challenges and Potential Applications of Nanotechnology

3.1 Nuclear Challenges

Public perceptions of nuclear technology hinge on two primary concerns: operational safety and radioactive waste management (Nuclear Energy Institute, 2014). Both tend to be attributed primarily to nuclear power although nuclear medicine, fundamental nuclear research, industrial uses of radioactive materials, and nuclear weapons ultimately pose the same issues. Although these two issues tend to drive the public discourse on nuclear, the spectrum of needs for continuing research extends not just to improving performance issues on existing power plants but also to finding alternative methods for supplying medical isotopes and achieving the scientific advancements that may one day make controlled nuclear fusion a practical option for generating power.

The roadmap for nuclear is referred to as "the nuclear fuel cycle" though along the way there are numerous "on-ramps" and "off-ramps" depending upon the application. Since every nuclear application (whether power generation, isotope production, medical imaging, industrial use, or high energy research) produces radioactive waste, all have the same end point so tracing the nuclear fuel cycle in reverse provides a way to highlight the points of departure and the differences by application.

3.2 Radioactive Waste Management and Environmental Cleanup

Uncontrolled release of radioactive materials into the environment represents hazards to human health and can adversely affect the surrounding ecosystems (Clean Energy, 2011). Early practices in dealing with radioactive waste were more of an afterthought than careful consideration of the full suite of possible negative impacts (Hamblin, 2002) (Long M. E., n.d.). Most countries now have regulations governing appropriate criteria for disposition of radioactive wastes and many are actively engaged in remedying legacy sites (Radioactive Waste Management, 2013). But regulations by themselves don't prevent accidents and

whether radioactive materials are dispersed into the environment inadvertently or by intent, there is a need for effective response tools.

Understanding the various types of hazards that radioactive materials can pose is necessary to developing effective responses. These hazards are primarily associated with exposure to ionizing radiation and toxicity but the effects of the various types of radiation and the wide range of physical and chemical characteristics of the materials that emit these different forms of radiation are key to the provisions that must be made.

General rules of thumb are: the shorter the half-life of the isotope the more intense the radiation emitted and decay to background levels takes 10 half-lives ("Radiation and Life," 2012). Thus, the radiation intensity (in counts per minute) from a given quantity of Co-60 (a gamma emitter with a 5 year half life) is less than that from the same quantity of technetium-99m (another gamma emitter with only a 6 hour half life). And it takes roughly 50 years for that mass of Co-60 to decay to background levels while technetium-99m decays to background levels in 60 hours ("Radiation Basics", 2013).

Alpha radiation is helium nucleus (two protons and two neutrons) often associated with transuranic elements. It is extremely energetic (because of the associated mass) and because it has both a large mass and a strong positive charge, interacts with matter in very short distances (it can be stopped by a thin sheet of paper). Although shielding requirements for alpha radiation are accordingly relatively minor, the hazards associated with ingestion or inhalation are significant because of the potential cellular damage to organs

in the immediate proximity caused by absorption of the high energy radiation. Many alpha emitters have very long half-lives (for instance plutonium-239 has a 24,000 year half-life) and readily form powders that can be dispersed by even a slight breeze ("Backgrounder on Plutonium", n.d.). In certain chemical form, these compounds are soluble in water and thus can contaminate surface and groundwater supplies ("Alpha Particles", 2013) ("Alpha Particle", 2014).

Beta radiation is an electron emitted from the nucleus, usually at vary high energy (in contrast with the

free electrons in metal matrices or valence electrons in an atom). These particles have the same mass and charge as an electron and though more penetrating than alpha particles, can be shielded with relatively small thicknesses of material. Beta emitters are found throughout the chart of the nuclides and thus exhibit the full gamut of chemical and physical characteristics of the chemical elements and their compounds. That means they can be dispersed as fine grain solids or dissolved in water ("Beta Particles", 2013) ("Beta Particle", 2014).

Neutrons are emitted in the decay processes of many isotopes and though they have mass equal to that of a proton, they have no charge and can penetrate great distances depending on their energy. Outside of nuclear reactors, the neutron fluxes produced by small quantities of materials that decay by this process are small in comparison and the probability of interaction is correspondingly low. Neutrons interact with small nuclei like hydrogen and hence water is quite effective in slowing them down and attenuating them. Neutron emitters tend to be found more frequently among the heavier nuclides (Neutron, 2014).

Gamma radiation and X-rays are photons often with very high energies and thus can penetrate substantial distances through dense materials like lead and concrete. Fission and activation products are among the strongest gamma emitters (Physics of Uranium and Nuclear Energy, 2012). Some, like Co-60, Sr-90, and Cs-137 have intermediate half-lives (less than 100 years), but others including some of the isotopes of iodine have very long half-lives ("Gamma Rays", 2013).

Thus, the criteria for disposition of radioactive waste have been developed in consideration of need for shielding, long-term isolation, and potential pathways into the active environment ("Disposal of Radioactive Waste", 2011). The main categories of radioactive waste are: High Level Waste (HLW), Low Level Waste (LLW), and Transuranic (TRU) Waste. Disposition of each must conform to the specific criteria that apply with regard to final waste form, packaging and handling, and transport ("Backgrounder on Radioactive Waste", 2011).

3.3 Conventional Practice in High Level Waste Management

Spent fuel from reactors and/or the first and second cycle raffinate and other waste streams from nuclear fuel reprocessing comprise High Level Waste ("High-Level Waste", 2013). Dismantled reactor components or processing equipment that have become activated by neutron exposure are typically considered Intermediate Level Waste and managed separately ("Radioactive Waste Management", 2013)

Against the current political backdrop in which the alternatives for nuclear waste disposition remain a hotly debated and completely unresolved issue, there is a temptation to conclude that no one had ever taken the time to think this all the way through. That isn't the case. At the time the Atomic Energy Act of 1954 was passed, there was a carefully planned and engineered "cradle to grave" sequence for uranium known as the "nuclear fuel cycle" that was modeled after the processes that had been used in the Manhattan Project to produce fissile material for weapons. Central to this was the extremely logical and practical assumption that "spent nuclear fuel" (which contains most of its original loading of fissile material) would be "reprocessed" to recover the unburned uranium and re-used to make new fuel. Furthermore, it was contemplated that the fissile plutonium-239 produced as a by-product in a process known as "breeding" would also be recovered and used as well ("International Atomic Energy Agency (IAEA)", n.d.) (S. Winston, personal communication, 2014).

However, in 1977, President Jimmy Carter made a unilateral decision that nuclear fuel reprocessing represented an unacceptable risk of nuclear proliferation and by veto of a funding bill (Carter, 1977) and subsequent Presidential Order (Andrews, 2008), effectively extinguished reprocessing as a viable part of the nuclear fuel cycle. Subsequent political actions effectively killed research on the breeder reactors that were designed to produce more fissile material than they consumed (Patterson, et al., 2010). The effect was to create what amounted to a dead-end that remains unresolved today.

Although President Carter's decision on reprocessing had the effect of stopping commercial reprocessing,

the practice continued at the Idaho Chemical Processing Plant (ICPP) until 1992 on fuel used by the US Navy for submarine and surface vessel propulsion ("Idaho National Laboratory Cultural Resource Management Plan", 2011). Furthermore, this technology had been a major element of the Manhattan Project. Consequently, there was and remains today large accumulations of residual contaminated liquids, known as first and second cycle raffinate (a product which has had a component or components removed) that contain most of the highly radioactive, gamma-emitting fission and activation products (Crowley & Ahearne, 2002, p. 54) (Winston & Marshall, 2012).

One method employed to convert these high level wastes to solid form was to spray it into a heated fluidized bed known as a "calciner" producing granular oxide pebbles that were then pneumatically transferred into giant steel underground tanks where it was believed they could be sufficiently isolated for long enough to constitute final resolution (Hancher & Suddath, 1961). Subsequent inspections of these tanks showed unexpected corrosion and further testing of the calcine product indicated a greater water solubility than had originally been thought ("Observations Concerning The Management of High-Level Radioactive Waste Material", 1967).

Another strategy for dealing with high level sludges stored in corroding tanks at the DOE's Hanford, WA, site is vitrification as a specially formulated type of monolithic glass. Among the persistent challenges in application of this approach have been the inherent friability (its tendency to fracture) of glass and the extreme chemical variability of the stored liquids (United States Environmental Protection Agency, 1992).
As is explained in the next section, most of the fissile U-235 that is used to make nuclear fuel does not get 'burned' before physical damage during reactor operation necessitates removal from the core. Commercial nuclear power plants typically shut down and refuel every 18 months replacing about one third of the core each time. For a 1000 MWe nuclear power reactor this amounts to roughly 60 to 70 fuel assemblies that after a "cooling" period in the co-located spent fuel canal, are now placed in shielded dry storage containers next to the reactor facilities (The Nuclear Fuel Cycle, 2012).

Literally thousands of these highly radioactive spent fuel assemblies have now accumulated at the 102 operating nuclear plants in the United States (Werner, 2012). This situation is not considered favorably by the public in general nor do the operators of these plants regard this as an appropriate solution (Nuclear Energy Institute, 2014).

After President Carter interrupted the nuclear fuel cycle, the US DOE began planning a permanent geologic repository for spent fuel and eventually selected a site in Nevada called Yucca Mountain. Literally billions of dollars were expended in designing, analyzing, testing, and constructing this facility which would have been the final destination for all the spent fuel now stored around the Country if President Obama had not effectively ended that project by Presidential fiat similar to that exercised by his predecessor Jimmy Carter ("Disposal", 2014). This further exacerbated the stalemate in "closing" the nuclear fuel cycle ("Obama dumps Yucca Mountain," 2009).

3.3.1 Potential Applications of Nanotechnology to High Level Waste

Although the political stalemate may continue indefinitely, there is a general consensus of opinion within the technical community that disposition of whole spent fuel assemblies is unworkable from a practical perspective. More than 99% of the original fissile material remains inside them; the decay heat load is huge and will remain so for decades to come; the radiation levels are so high that they must remain inside concrete shielding at all times; and because of the severe conditions endured within the core during their operational service, there is reason to question how long the physical integrity of the assemblies can be maintained before failures begin occurring and releasing highly radioactive materials into their surrounding environs. And perhaps the most obvious problem is their sheer size; a typical Pressurized Water Reactor (PWR) fuel assembly is about 14 feet tall, about 18 inches square and weighs a half a ton (Agreements abound at France-China Summit, n.d.) (Feiveson, et. al., n.d.).

Presuming that nuclear proliferation issues will continue to politically preclude consideration of reprocess-

ing (a debatable proposition), there still remain practical options for breaking down spent fuel and separating its constituents into categories that are practical to manage. The long lived isotopes can be separated from those of intermediate half life. The gamma emitters can be segregated from the alpha emitters. The gaseous fission products can be extracted and immobilized; the water-soluble materials can be reacted with compounds to make them insoluble; and the actinides (most which comprise the fissile that causes proliferation concerns in the first place) can be processed in a way that would render any diversion for weapons purposes both dangerous and impractical (S. Winston, personal communication, 2014).

Nanotechnologies could serve such a process in several key ways. Nuclear fuel is a solid material that must be dissolved in nitric acid to get at its constituents. Conventional methods for separating these constituents would involve a succession of counter-current organic/aqueous phase extractions that generate large volumes of radioactively contaminated liquids (Agreements aound at France-China summit", n.d.). A nanomaterial called graphene oxide has been synthesized by Tour, et al at Rice University (Tour, et al., 2013), which has been demonstrated to quantitatively remove actinides from aqueous solution without the need for any other type of extractant.

Interviews with Dr. Tour and his collaborators confirmed that not only is graphene oxide extremely effective, it works very rapidly as well. And compared with conventional separations techniques, its effectiveness does not appreciably diminish as the concentrations get progressively smaller and smaller at the tail end of the process(Tour, et al., 2013).

Perhaps the most intriguing aspect of graphene oxide is associated with its size and composition. Each flake is a few micrometers across and only one atom layer thick. That gives each flake several thousand times more reactive surface area than any comparable purpose conventional absorber or ion exchange media. Because of its extreme hydrophilicity (the tendency of a molecule to be solvated by water), it is fully soluble in aqueous solution and when thus dispersed, quickly surrounds any dissolved actinides (as opposed to fixed filter media that have to wait for the dissolved molecules to come to them). After the

flakes are saturated with actinides (all reactive sites occupied), they can be extracted through nanoporous ceramic cross-flow filters that allow only water to pass through. This leaves a small volume of graphene oxide laden with actinides. And because the graphene oxide is made up of carbon and oxygen it can be burned off leaving behind just the actinides (J. Tour, personal communication, 2014) (Tour, et al., 2013).

Volatile fission products can extracted from spent fuel by grinding and then heating the pellets. Then these can be captured and isolated using metal organic frameworks (MOFs) developed by Dr. Tina Nenoff of Sandia National Laboratory (Sandia National Laboratories, 2013). These MOFs are capable of absorbing and binding massive quantities of radioactive gases such as iodine-129. Radioactive iodine isotopes are one of the more problematic products of nuclear fission because they form a highly mobile volatile gas and have a half-life of 15.7 million years.

Dr. Nenoff has demonstrated that the MOF developed by her team (called ZIF-8) can bind up to 125 weight percent iodine, more than ten times as much as conventional zeolites. This particular MOF has pore size of less than one nanometer in diameter which allows the iodine diffuse in but prevents it from being released unless the material is heated above 300 °C. This means that it can be incorporated into a low-temperature vitreous final waste form without releasing its content. These MOFs are now being tested at Oak Ridge National Laboratories (Nenoff, et al., 2011) ("MOFs ready to gulp up radioactive iodine gas", 2011).

Although several of the volatile fission products in spent fuel are amenable to binding by chemical reaction, the noble gases like xenon and krypton are generally not because of their stable outer electron shell. However, in the early 1960s Bartlett discovered that platinum hexafluoride had sufficiently high electronegativity to form reactions with some of the higher atomic mass noble gases (Christe, 2013, p. 4588). Subsequently, work by Dr. Peru Jena et al has led to the development of nano compounds called hyperhalogens that greatly increase this electronegativity to the point that such materials might be practical to employ as "getters" for these otherwise chemically inert gases (Puru, et al., 2010, pp. 8966-8970).

A possible improvement in vitrification of liquid wastes may be in the form of nano-silicates which have been demonstrated to increase the heat resistance of glass, reduce its permeability to water, increase its ductility (reducing friability), and broaden tolerance to variations in formulation (Gleiter, 2013, pp. 517-533). Long-term isolation of actinides is discussed in the ensuing section on transuranic wastes.

3.4 Conventional Practice in Low Level Waste Management

Low Level Waste includes items that have become contaminated with radioactive material or have become radioactive through exposure to neutron radiation. This waste typically consists of contaminated protective shoe covers and clothing, wiping rags, mops, filters, reactor water treatment residues, equipment and tools, luminous dials, medical tubes, swabs, injection needles, syringes, and laboratory animal carcasses and tissues. The radioactivity can range from just above background levels found in nature to very highly radioactive in certain cases such as certain parts from inside the reactor vessel in a nuclear power plant. Low-level waste is typically stored on-site by licensees, either until it has decayed away and can be disposed of as ordinary trash, or until amounts are large enough for shipment to a low-level waste disposal site in containers approved by the Department of Transportation (Radioactive Waste, 2014).

Early practices for dealing with LLW were to dig a hole and bury it without employing any engineered features at all. Over time these practices were upgraded, first by placing in poly-lined steel drums (which then got crushed by the bulldozer covering them with dirt) and later by placing it in large concrete containers prior to burial. Consolidation and compaction were adopted to reduce disposal volumes and incineration has been (and continues to be) employed. Shallow land burial continues to be employed today with establishment of exclusion zones to prevent inadvertent intrusion, provisions to prevent burrowing animals from tunneling through the buried waste, and features to minimize potential for percolation of surface waters. Siting criteria are used to mitigate effects of groundwater intrusion and minimize the possibility of groundwater presence (“Low-Level Radioactive Waste”, 2011).

3.4.1 Potential Nanotechnology Applications for Low Level Waste Management

The term "Low Level Waste" does not necessarily mean that the radioactivity levels are low nor does it necessarily mean the half-lives of the radioactive materials are short. It's simply a classification based on consideration of a large number of complex factors intended to segregate wastes with certain characteristics from others. The need for long-term isolation from the active environment is as important as for any other radioactive wastes and appropriate shielding likewise applies (Radioactive Waste, 2014).

Because the siting criteria for LLW are less stringent than for HLW (if a consensus could ever actually be reached on exactly what those are), the primary container is the main line of defense for preventing incursion by water, burrowing animals, or plant roots. Metal drums are at best a short term container and concrete is subject to cracking and is not impermeable to water.

Among the claims made for a recently filed patent application by Roddy (Roddy, et al., 2011) using nano-structured clay as an admixture is a major reduction in the water permeability of concretes. Increases in tensile strength (not a typical concrete attribute) reported by Sasmal (Sasmal, n.d., pp.117-129) may offer solutions to the notorious tendency of concrete to crack as a result of thermal expansion or shrinkage during curing. Both of these attributes could enhance confidence in the durability of the containers for LLW and in their long-term ability to prevent water from percolating through waste or intrusion by burrowing animals.

3.5 Conventional Practice in Transuranic Waste Management

Transuranic (TRU) waste is radioactive waste containing alpha-emitting radionuclides of atomic number greater than 92, half-life greater than 20 years, and activity greater than 100 nanocuries per gram of waste. The isotope that dominates siting considerations for a permanent disposal facility for TRU waste is plutonium-239 which has a half-life of 24,100 years. Using the "ten half-life to background" rule of thumb, the

disposal integrity must be maintained for 241,000 years ("Characterzation of remote-handled transuranic waste...", 2002). While this is more than 20 times longer than the history of civilization, it is an order of magnitude less than the estimated time that some form of hominid has been on earth. Hence, while as yet no engineered structures ever built (including the pyramids in Egypt) have survived without significant deterioration for even a small fraction of this time span, it would be irresponsible not employ the best of the current methods to make the attempt.

In the 1950s it was recognized that there are geologic formations such as salt domes that have remained stable for millions of years. It thus logically followed that these might be suitable candidates for building subterranean vaults in which these wastes might reasonably expect to remain undisturbed for a comparable period. In 1979, the US DOE began work on the Waste Isolation Pilot Plant in a massive salt formation near Carlsbad, New Mexico. Waste is placed more than 2000 feet underground in "rooms" that have been excavated in the midst of a 3,000 foot thick salt formation that has been stable for more than 250 million years. Warnings are posted on the surface in the surrounding area to deter any future drilling or excavation (Office of Environmental Management, n.d.).

Such massive salt beds have a long-term semi-plastic characteristic under the immense pressures at these depth below ground surface. Any holes or cracks that may form are expected to seal back up as a result and even the "rooms" in which the waste is placed will ultimately collapse and fill all the surrounding voids permanently entombing the material ("Energy.gov," n.d.).

Until 2014, there were no indications that this expectation was unfounded, but in February, trace amounts of americium and plutonium were found on the surface more than a half a mile away from the facility ("Waste Isolation Plant Recovery", 2014). At present, the cause of this has not been determined.

3.5.1 Potential Nanotechnology Applications to Transuranic Waste Management

In 1985, Smalley and his research group discovered a "cage" form of carbon nano molecule that looked like the geodesic domes famously associated with Buckminster Fuller and accordingly dubbed "fullerenes" or "buckyballs" (Smalley, 1996). These molecules exhibit an extremely high chemical stability (greater than diamond, for instance) and have an observed affinity for incorporating electronegative molecules inside them. Collaborative work between Los Alamos National Laboratory and Rice University in 1997("The Actinide Research," 1997) consisted of a potentially novel means for isolating actinides like those that comprise TRU Waste.

3.6 Separations Process

Separations processes (in the context of the nuclear fuel cycle) are generally (but not necessarily) associated with nuclear fuel reprocessing (or "recycling" as it is called in current parlance). Though historically the dominant use of reprocessing was to recover fissile material from spent nuclear fuel to either further refine it to make weapons or to re-use in new nuclear fuel, it is also a key step in making radiopharmaceuticals. In both cases, the material is not typically radioactive until it undergoes nuclear reactions either in a reactor or as a target for an accelerator ("Agreements abound at France-China Summit, n.d.).

After irradiation, the desired product is heterogeneously co-mingled with a lot of other by-products and virgin material. In most cases, the target or the nuclear fuel is in a solid metallic or ceramic matrix that must be dissolved to separate its constituents. Conventional practice is to use a strong acid often in conjunction with heat, electric current, or other extremely aggressive acids to reduce the solid to a liquid solution. The next step is to add chemicals that specifically alter the valence of the desired element to reduce its solubility in aqueous solution (the acidic liquid) and increase its solubility in another immiscible solvent (an organic fluid). Then the aqueous solution and the organic fluid are forced to flow countercurrent to one another through pulsed columns that thoroughly mix them. Because the desired element has been adjusted to

chemically prefer dissolution in the immiscible (not forming a homogeneous mixture when added together) organic phase, it partitions out of the aqueous phase and into the organic phase. Once most of the desired element has been extracted into the organic phase, the fluids are allowed to settle which, because the organic phase and aqueous phase are immiscible, allows decanting into distinctly separate solutions. The aqueous phase is known as the first cycle raffinate (S. Winston, 2014) (Long J. T., 1978).

Then the organic phase is treated with chemicals that adjust the valence of the desired element back to preferential solubility in aqueous solution and the process is repeated only using clean water. This time the desired element extracts back into the aqueous phase. The process can be repeated successively until the desired purity is reached but each repetition generates more volumes of radioactively contaminated liquids, both organic and aqueous.

The first aqueous phase that settles (first cycle raffinate) typically contains most of the water soluble fission products like cesium-137 and strontium-90 and activation products like iron-59 and cobalt-60 in high concentrations. The first organic phase that settles still contains some of these fission and activation products so generally this process is repeated several times.

3.6.1 Potential Nanotechnology Applications to Separations Process

Because the first cycle raffinate is an aqueous solution it may be amenable to treatment using graphene oxide to remove fission products (described in the previous section on LLW). This would eliminate the need for counter-current organic extraction and the attendant volume of liquid waste from the multiple passes necessary to achieve desired purity.

3.7 Irradiation

Irradiation can be done either in a nuclear reactor or with an accelerator and is fundamentally the bombardment of material with high energy subatomic particles such as neutrons, protons, electrons, or photons.

Because atoms are mostly empty space and shrouded with a cloud of electrons, the likelihood that any single particle will interact with a particular atom nucleus is small. Neutrons have the best chance of interacting with a nucleus because lacking an electrical charge they are not repelled by the positively charged nucleus (the "Coulomb barrier") or the surrounding electron cloud and because they have mass they can stick to the nucleus if they hit it at the right speed (Brian & Lamb, 2000) (Radioisotopes in Medicine, 2014).

Protons have a harder time colliding with the nucleus because their charge is the same as the nucleus which tends to repel them, but, with sufficient energy that can be overcome. Electrons only have a small fraction of the mass of neutrons and protons but have equal but opposite electric charge. Their biggest challenge is in running the gauntlet of the electron cloud, but if they get past that (and some do) they have a very good chance of being electrically attracted to the nucleus. Photons have neither mass nor charge but they can carry a lot of energy which in turn affects whether the nucleus will stop them or let them zip on through.

Every nucleus responds differently to interactions with subatomic particles. Some, like uranium-235, have such a crowded nucleus that there's just no room for anything more. If a stray neutron hangs around too long (measured in femtoseconds), the whole thing blows up releasing neutrons and showering its surroundings with chunks of protons and neutrons stuck together (fission fragments). That event is called fission. But there a lots nuclei that are more than willing to harbor a passing neutron and kick something else out of the nucleus to make room for it. This event is called capture and is generally followed by the emission of energy in the form of a gamma photon or the expulsion of what amounts to an electron in the form of a beta particle. Sometimes, more rarely, it will boot out a proton or in other instances it will kick out two protons and two

neutrons.

Enumerating all of the possible sequences that can occur in a nuclear reaction would require volumes (and comprise the subject matter for entire fields of study). Suffice it to say that irradiation can result in fissions releasing an immense amount of energy while producing a wide variety of new (generally radioactive) elements and in transmutations that also produce a wide variety of new (generally radioactive) elements. This makes irradiation an extremely powerful tool for accomplishing what the original alchemists had only dreamed of doing. When uranium-238 captures a neutron it becomes uranium-239 then quickly decays to plutonium-239, a fissile element that can be used to make nuclear weapons. When molybdenum-100 captures a proton it becomes technetium-101 and quickly expels two neutrons to become technetium-99m the diagnostic tool used in nuclear medicine for more than 40 million procedures a year.

3.8 Designing and Building an Irradiation Machine

Whether an irradiation machine is an accelerator or a reactor, the challenges include keeping everything together, creating the necessary ambiance for the magic to happen, and managing the inevitable mess that results when the magic happens.

A reactor is a complex assembly of nuclear fuel arrayed in a very specific geometry with interspersed control rods and spaces through which coolant/moderator can flow. The components including the fuel assemblies, the supports, the primary vessel, the instruments, the control rods and drives are all subjected to extreme pressures, highly localized extreme temperatures, intense radiation from neutrons, gamma radiation, violent ballistic forces at a molecular level, corrosion, and mechanical forces. The materials of construction have to be compatible with the conditions necessary to sustain the reaction, that is, they can't soak up too many of the neutrons but they have to keep them from escaping, they have to conduct the heat away from the fuel pins, they have to retain their strength at all times, and they have to resist degradation over time (Santoro, n.d.).

Accelerators come in all different sizes in a wide variety of configurations ranging from the 17 mile diameter Large Hadron Collider in Europe to desktop synchrotrons in laboratories. There are linear accelerators that magnetically push electrons down a long evacuated tube and smash them into a target. There are cyclotrons that whirl protons around a giant spiral and pull them off at different points down a beam line to impact on targets. Making an accelerator work requires the ability to time switching events in almost infinitesimally small fractions of a second, precise alignments, and innovative strategies for sustaining a high enough beam current (flux) to achieve the desired nuclear reaction while drawing off the resultant heat fast enough to keep from annihilating the target. Like the conditions for components in a reactor, accelerators can also subject components extremely severe conditions ("Accelerators for Society", n.d.).

In both cases, creating the "ambiance" necessary to induce the desired reactions boils down to manipulation of complex variables at the scale of atoms. Consider the challenge of making a medical isotope like technetium-99m. There are several strategies for making it, but to be acceptable for use in patients it has to meet certain standards of radiological purity and specific activity. The "m" signifies that this particular isotope is meta-stable distinguishing it from its also-radioactive-almost-twin-sibling, technetium-99 which takes thousands of years to decay. The "m" also means that technetium-99m has a very short half-life (~6 hours depending on dose) and that's one of the things that makes it so attractive for medical imaging because it decays away rapidly in a person minimizing the collateral cellular damage from radiation (Technetium-99m, 2014).

But the short half-life creates production challenges as well—the rate of production has to be greater than the rate at which it decays. (The point where production exactly equals the decay rate is called "secular equilibrium".) Achieving the desired rate would be challenging enough if it was a purely deterministic process, but it's not—it's entirely probabilistic. The nucleus of an atom and every subatomic particle that comprises it exist solely in the strange realm of pure quantum mechanics.

Protons and neutrons aren't "solid" objects in the sense might be attached to a billiard ball. Instead they

are "fuzzy" things that have characteristics of a wave for which the simplest analog might be a jump-rope. When twirled at a constant speed (frequency) with the right distance between the top of the loop and the bottom (amplitude), it is possible for a person of the right height (less than the amplitude) to run (at a speed matching the frequency) right through without being touched by the rope. And that only works if timed at just the right point in the arc of the rope (S. Winston, personal communication, 2014).

At the scale of atoms and subatomic particles, this wave characteristic is described by a mathematical "probability distribution function" that is governed by the Heisenberg uncertainty principle. This states that it is impossible to simultaneously specify a precise position in space and momentum of a particle. Since momentum is proportional to the product of mass and the time derivative of space, that means exactly where a proton or a neutron actually is at an exact moment in time can never be known precisely (Clark, 2007). But you can have a general idea where it might be most of the time.

Going back to the jump-rope analogy, that means that both the target nuclei and the bombarding subatomic particles are vibrating in complex ways that may be parallel to one another or at some angle and continuously changing. Those vibrational or wave characteristics also change relative to the amount of energy that particle has, but those changes can only occur in discrete packets or "quanta" that correspond to the allowable harmonics (governed by the length of the jump rope) of the particle (S. Winston, personal communication, 2014) (Kiger, 2011).

What does that mean in practical terms? Simply put: the chances of a subatomic particle interacting with a nucleus are small and depend on coincidence of their respective probability density functions. In other words, running through the jump rope at a speed that coincides with the rate at which it is being twirled. Exact synchronicity allows the jumper to enter the space of the twirling rope and as long as each jump continues to coincide with the period of the swinging rope there is no interference. By analogy, if a subatomic particle enters the "space" of a nucleus at the right energy it can "resonate" with the nucleus (stay in that same space) as long as it doesn't disturb any of the other occupants of that space.

So the first part of the challenge is to create a target that can be hit. The second part of the challenge is directing subatomic particles with the right energy to hit the target. Knowing that atoms are mostly empty space to begin with, it is necessary to pack as many target atoms in as small a volume as possible. Then this volume has to be oriented precisely in the path of as many subatomic particles as can be directed at it at a time. Fortunately, it isn't hard to collect trillions of atoms but sorting them down to a collection of just one single isotope requires a great deal of effort and special equipment. This process is called "isotopic enrichment" and involves first chemically isolating one particular element then exploiting mass differences among the various isotopes of that element to select and collect one particular one ("Isotope Separation", 2014).

Once the target is assembled, then means have to be devised to direct the right subatomic particles at it at the correct angle at just the right speed (energy). The brute force method is to place the target inside a nuclear reactor where at steady state operation there are trillions of neutrons flying all over the place in every possible direction. Sooner or later a neutron of the right speed and angle crashes into a nucleus of the target with a coincident set of quantum conditions and an interaction occurs. If the population of target atoms is large enough (traditionally achieved by using highly enriched uranium) and if the number of incident neutrons is large enough, these interactions begin converting the target atoms into new isotopes faster than they decay away (Kiger, 2011) ("Nuclear Power Reactors", n.d.).

Achieving all of that only creates the initial conditions to enable reactions to occur; maintaining those conditions in order to sustain the reactions are the next challenge. In other words, "continuously cleaning up the mess" that the reactions make as they occur. The basic reactions that can occur are fission and "capture". Both result in release of heat energy and fission produces a statistical distribution of broken pieces of the original nucleus that become new elements, most of which are not the desired product and some of which parasitically soak up neutrons without advancing the intended purpose. The heat energy has to be removed or the temperature of the entire assembly will rise to the point that it melts or disintegrates. And something has to be done with the debris from the reactions or the clutter eventually accumulates to the point that nothing further can be accomplished.

Now consideration of the production options can begin. Fission of uranium-235 will deliver a predictable yield of technetium-99m's parent molybdenum-99. That in turn will decay to yield a steady, predictable quantity of technetium-99m. To get the optimal density of uranium-235, it is necessary to have a specified enrichment of that particular isotope ("Frequently asked questions, n.d.). Then the target has to be placed in a position inside the reactor where the flux of neutrons of a particular energy is the greatest. The neutrons bouncing around inside the reactor can be reduced to the average energy optimal for the reaction to occur by collisions with small nuclei (moderated) and the heat can be removed by intimate circulation of a heat transfer medium. Water turns out to be very effective for both purposes because it contains lots of hydrogen atoms (with a single proton for a nucleus) and it has a large heat capacity (S. Winston, personal communication, 2014).

Once all these conditions are established, the target remains inside the reactor until the desired specific activity is reached (usually very close to the point of reaching secular equilibrium). At that point the target can be removed from the reactor, dissolved, and the parent molybdenum-99 can be extracted and purified for loading into a specially designed container for delivery to hospitals ("Frequently asked questions, n.d.).

Another production option is to perform a comparable process using an accelerator. One strategy is to fabricate a target out of highly enriched molybdenum-100 and bombard it with high energy protons from a cyclotron. This results in capture of some of the protons to make technetium-101 which quickly expels two neutrons to make technetium-99m. As with the fission reaction in the reactor, the target density of Mo-100 has to be very high as does the flux of incident protons. And both the target nuclei and the incident protons have to be at the right energy level to maximize the probability of a reaction. Even under the best of conditions, far more of the incident protons just glance off the target molecules than react but each glancing blow deposits some of the energy carried by these protons heating up the target. So target cooling is very important not just to prevent it from disintegrating but also to keep the internal energy of the target atoms in the right energy state ("Accelerators for Society", n.d.).

The space in front of an accelerator target has to have a clear path for the particles to pass without interference, meaning that it must be evacuated. The only mechanism of heat transfer that works in a vacuum is radiant and that would require intolerably high target temperatures to dissipate the amount of parasitic heating that occurs. So cooling has to be accomplished by conductive and convective heat transfer on the backside of the target. And this circulating coolant necessarily also gets exposed to the incident beam because far more of the incident particles pass through the target than actually react with it or are parasitically absorbed ("Accelerators for Society", n.d.).

Generation of power from nuclear fission involves the same principles except instead of irradiating targets, fuel assemblies are irradiated in a self-sustaining reaction. These fuel assemblies generally comprise rectangular arrays of long tubes about ½ inch in diameter filled with uranium oxide pellets. The tubes are typically made from a zirconium alloy held in place within regularly spaced grids at intervals along the vertical length of the assembly. The assemblies are then arranged next to one another to form a mosaic array that approximates a circle in cross-section. Control rods that contain material that absorbs neutrons (called neutron poison) are interspersed within the array to enable the operators to shut down the reactor and regulate its power. Water is circulated through the array to pick up the heat from the nuclear reactions and moderate the neutron energy as they are produced. The circulating water passes through an external heat exchanger that produces steam to drive a turbine-generator and is then pumped back through the reactor core (Nuclear Power in the World Today, 2014) (The Nuclear Fuel Cycle, 2012).

The fuel used in commercial nuclear reactors has a fairly low enrichment of the fissile isotope uranium-235 (typically around 3.5% enrichment) and must be replaced roughly every 18 months. Interestingly, refueling of reactors is not because all the fissile material gets exhausted, in fact only about 0.7% of it actually undergoes fission. The driving factor fuel replacement is actually the mechanical damage that a fuel assembly experiences in the severe environment inside the reactor core (Nuclear Fuel Process, 2014).

This damage has many causes, the most violent of which are the result of the nuclear reactions (as might be

expected). Although fissions occur in individual atoms, the localized effects on the surrounding solid lattice are enormous. Because the energy released when a single atom fissions is approximately 10 million times greater than that released in any chemical reaction (i.e. burning gasoline) and because the event is instantaneous, the surrounding atoms have neither the heat capacity to absorb this immense release of energy nor the time to dissipate it to their neighbors. Consequently, the localized temperatures can get as high as 2000 °C (The Science of Nuclear Power, 2014).

This heat has to be transferred by conduction to the outside surface of the fuel, across the narrow gap between the pellet and the cladding material (the tube), through the cladding, and then transferred by convection to the water circulating on the outside of the cladding. Because there is more uniformly dispersed fissile material in the center of each pellet than around its periphery, the center line temperatures can rise to a steady-state level approaching the localized temperatures surrounding each fission (Physics of Uranuim and Nuclear Energy, 2012).

The distance that the heat has to travel from the pellet center line to the outside wall of the cladding tube is only about ¼ inch and that is effectively in dynamic thermal equilibrium with the coolant. In a pressurized water reactor (PWR), the coolant runs at about 330 °C so the temperature differential from the pellet centerline to the cladding wall is on the order of 1700 °C. All solid materials expand and contract in relationship to temperature (in accordance with their own unique material property known as the coefficient of thermal expansion), and this huge difference over an extremely short distance results in correspondingly high stresses within the fuel matrix. Like a concrete sidewalk with no expansion joints in the hot sun, the fuel matrix ends up riddled with cracks (Gittus, 1972).

But thermal stresses aren't the only cause of damage. When an atom of uranium fissions, the fragments of its nucleus are propelled away at extreme velocities. These fission fragments have more than enough momentum to knock any atoms in the fuel matrix out of position when they collide with them. In turn the displaced atoms careen around the matrix like balls on a pool table knocking other atoms out of position.

Although all the atoms displaced eventually find a new position in the lattice, the integrity of the lattice itself gets continually reformed with progressively less integrity as the process continues. Damage from this effect is measured in the number of times an individual atom gets knocked out of position and is known as "displacements per atom" or "dpa". Typical spent fuels have received up to 100 dpa during the relatively brief time they spend in the core (Radiation Basics, 2013).

Another cause of stress in the fuel matrix is the build up of fission gases. Some of the fission products formed are noble gases such as xenon and krypton. Unlike solids and liquids whose specific volume changes only slightly as a function of temperature, the volume that gases occupy and the pressure within vary in direct proportion to temperature. Since the volume inside the fuel assembly is fixed, there is no other option except for the pressure to increase. This internal pressure is additive to the stresses previously described (Radiation Basics, 2013) (The Nuclear Fuel Cycle, 2012).

The final contributor to fuel damage is in the form of mechanical forces. One of the effects of the pressure build-up from fission gas accumulation is swelling of the fuel pellet. This expansion can continue until the narrow gap between the pellet and the inside of the tube no longer exists and the pellet is pressed against the tube wall. Because the tube walls aren't thick, this can produce bulging along the axis of the tube everywhere except at the assembly grid supports (The Nuclear Fuel Cycle, 2012) (S. Winston, personal communication, 2014).

Another mechanical effect is vibration. No matter how carefully the reactor is engineered and operated, transient conditions arise that can cause flow instabilities in localized areas of the core. The resultant differential flows can create asymmetries in pressure along the length of the tube causing it to flex back and forth.

Fuel, and in fact, the entire reactor core can be damaged if coolant flow is interrupted. These so-called Loss of Coolant Accident (LOCA) scenarios are a major focus in assuring reactor safety. The problem is not

getting the reactor shutdown and stopping the nuclear reaction—the control rods quickly and efficiently accomplish that purpose. The problem is dealing with the decay heat of the fission products and activation products in the core. These continue to generate an immense amount of heat long after the nuclear reaction stops ("Resolution of Generic Safety Issues," 2013).

If the core cannot be adequately cooled, the temperature rises until it reaches equilibrium with its surroundings. The zirconium alloy used as cladding in most nuclear reactors is an ideal material for its purpose at temperatures less than 1000°C because it has high strength and more importantly, it is almost transparent to neutrons at thermal energies. However, when the temperature climbs above 1000°C, the zirconium starts to become very reactive, ultimately reaching a point where it will pull oxygen away from water molecules to oxidize. That releases a mole of hydrogen for every mole of water and zirconium that react. If the hydrogen accumulates inside the reactor containment building it represents an explosion hazard if air is admitted.

The foregoing scenario is exactly what happened at Fukushima Dai-ichi ("Extraction of Fukushima groundwater starts", n.d.). The reactors all shut down as they were designed to do when the earthquake occurred. But when the resulting tsunami overwhelmed the seawall and swamped the back-up diesel generators that were maintaining coolant flow through the reactor, the cores began to overheat. When the temperature got too high, the zirconium cladding began to oxidize releasing an additional load of heat that caused a snowball effect. The hydrogen gas accumulated in the containment building until it reached what is known as the lower explosive limit (LEL) and the resulting explosion essentially destroyed the building (Fukushima Accident, 2014).

Mechanical damage isn't the only consideration regarding how long fuel can remain in the core before it needs to be replaced. The other factor is reactivity. As previously described, less than one percent of the fissile material in commercial reactors actually fissions before the fuel has to be replaced. But the reactivity of the core has degraded. The cause is the build-up of fission products in the core. Some, like xenon-135 in

particular have a huge thermal capture cross-section (that means a high probability of capturing a thermal neutron) and although it decays fairly rapidly (9.2 hour half-life) it can have a dramatic impact on the ability to make power changes. Other longer-lived isotopes like samarium-149 and a collection of fission products called "lumped fission product poisons" are orders of magnitude less of an effect on reactivity than xenon-135, but in time accumulate to the point that the full range of normal operating options begins to be compromised (The Nuclear Fuel Cycle, 2012).

3.8.1 Potential Nanotechnology Applications for Irradiation

In some ways, nanotechnology has always been an imperative for sustaining nuclear reactions: the process for making nuclear fuel starts with grinding uranium oxide powders to an average size less than 100 nanometers. Beyond that, however, the number of state-of-the-art nano scale techniques and materials that are being exploited by the nuclear industry remain quite limited. That circumstance is already beginning to change, even if somewhat randomly.

3.8.2 Potential Nanotechnology Applications for Hydrogen Generation

While there were many contributing causes to the accident at Fukushima Dai-ichi, the explosion that ultimately led to release of radioactive materials to the environment was due to accumulation of hydrogen inside the containment building. Hydrogen concentration in air is very difficult to measure, but accumulation to the LEL can be prevented if it can be detected and dissipated at the rate it is produced. Hydrogen is the lightest gas and one of the most readily reactive. A hydrogen selective nano structured membrane has been developed at Swansea University by Dunnill and colleagues ("Charles Dunnill", n.d.) that not only provides a reliable, highly accurate measurement of hydrogen but also can serve as a one-way conduit for capturing and transmitting hydrogen. Coupling a "collector" based on this membrane with an external flare (like those conventionally employed at petroleum refineries) would allow the hydrogen to be harmlessly burned to water as it is produced instead of building up (A Barron, personal communications, 2014).

Because of its nanoscale structure, the number of transmissive pores per unit area is extraordinarily high enabling a relatively small total surface to capture vast quantities of hydrogen. That means that a system based on this membrane engineered at the right size could have the capacity to keep pace with even the extreme rate of hydrogen generation that results from a zirconium-water reaction at high temperature (International Atomic Energy Agency, 1998-2002).

3.8.3 Potential Nanotechnology Application for Fuel Cladding

Long before the events at Fukushima Dai-ichi occurred, it was recognized that the zirconium alloy used for cladding posed the risk of high temperature reaction with water. The mitigating strategy was to attempt to anticipate every possible mechanism that could result in loss of coolant to the reactor core and engineer preventive responses. So far, as this accident and the one at Three Mile Island Unit II in 1979 demonstrated, no amount of imaginative anticipation has been sufficient to cover every possibility resulting in loss of cooling. So the emphasis has now switched to making the fuel assemblies themselves more tolerant to high temperature excursions. One approach to designing so-called Accident Tolerant Fuels (ATF) is to find an alternative to use of zirconium as a cladding material (Griffith, 2013). Another is to devise a means for coating the cladding with a durable, temperature tolerant, impermeable material that won't crack or flake off (S. Maloy, personal communications, 2014).

Finding an alternative to zirconium alloys is not a trivial exercise because in so many ways it is ideal for this particular application. Thermal neutrons go right through it like light through glass—most other materials are nearly opaque to thermal neutrons. Zirconium alloys are strong and malleable, an important feature for a long, thin-walled tube subjected to so many simultaneous forces. They also are good conductors of heat, which is key not only to efficiently generating steam but also to help reduce the thermal effects on the fuel itself ("Zirconium Cladding," 2013).

With the current emphasis on improving accident tolerance of fuels, the potential benefits of nanotech-

nology for improving cladding materials are being actively explored. There are federally funded research programs at Los Alamos National Lab, Oak Ridge National Lab into oxide dispersion strengthened (ODS) steels (Bhattacharyya, 2012, pp. 1-19), public-private collaborations between industry and federal research institutions (called Cooperative Research and Development Agreements or CRADAs) examining nanostructured silicon carbide (SiC), and entirely privately funded research into nanostructured graded interfaces (A. Barron, personal communications, 2014). Wolfgang Hoffelner has examined the possible benefits of utilizing nanostructure zirconium particles in the production of cladding (Chen, 2013, pp. 688-694).

3.8.4 Potential Nanotechnology Applications for Nuclear Fuel

Nuclear fuel is subjected to some of the harshest conditions that have ever been produced on this planet. Accordingly, better materials and better fabrication techniques have been the subject of research since the advent of nuclear. Recently, nanotechnologies have been embraced among those avenues meriting exploration.

To address the huge temperature differentials inside a fuel pellet Professor James Tulenko at the University of Florida has explored a wide variety of novel nano scale formulations and techniques. Among these experiments are inclusion of nanodiamonds (Tulenko, et al., 2010), carbon nanotubes (Sundar, et al., 2013, pp. 1-14), nanoscale magnesium particles, and silicon carbide (Tulenko, et al., n.d.). Similar investigations have been performed with nanoscale inclusions of beryllium oxide by McCoy and Mays (McCoy & Mays, 2008, pp. 157-167).

Additive manufacturing (3D printing) using nanoscale powders is being examined by Gardner (Gardner, 2014) as a possible avenue for achieving the same target densities in fuel as conventional methods, but allowing for incorporation of engineered features like tailored porosity to facilitate collection of fission gases, preferential thermal conduits to dissipate heat, and strategic placement of grain boundaries to serve both as collection points for voids and to relieve accumulated stresses.

3.8.5 Potential Nanotechnology Applications for Heat Transfer

Many industrial processes use water as a heat transfer medium including coal and gas fired power plants and of course nuclear power plants. A major parameter governing the rate of heat transfer in the temperature-pressure regimes where water changes phase from liquid to gas is called "critical heat flux". This is the point where the rate of heat conduction through the tube wall of the heat exchanger exceeds the convective capacity of the liquid water to carry heat away. At that point (known as Departure from Nucleate Boiling or DNB) the water forms a vapor film on the outside of the tube. Because vapor phase convection is much less effective than liquid phase convection, when this happens the tube can actually get so hot it melts ("Heat Transfer", 2014).

Two nanoscale strategies have been examined to improve DNB in nuclear reactors. The first is to enhance the thermal conductivity of the primary coolant (the water) by addition of a small percentage of nano-metals or carbon nanotubes (Sundar, et al., 2013). Other approaches either etch nano-scale grooves into the surface of the tubes or attach carbon nanotubes (Chiavazzo & Asinari, 2011, p. 249) often referred to as "nanofins". In either case the effect is to create an expansion of the surface area for heat transfer within the boundary layer on the outside of the tube. While this avoids disruption of the fluid dynamics it greatly increases the amount of heat flux before DNB.

One of the effects of neutrons that applies not only to the fuels but also to the other reactor components including the primary vessel, is embrittlement. Work by Stuart Maloy with ODS steels shows considerable promise for mitigating the damage and potentially extending the useful life of reactors (S. Maloy, personal communication, 2014).

3.8.6 Potential Nanotechnology Applications for Shielding

Radiation shielding generally exploits density and mass to attenuate radiation and is consequently heavy and bulky. While this can be accommodated within a fixed facility, it complicates shipping of radioactive materials. For interstellar and earth-orbiting satellites that have radiation sensitive instruments and especially for human space flight, both weight and space are at a premium. At NASA Langley Research Center, Dr. Catharine Fay has been leading a research team exploring the use of nanostructured materials to diffract or reflect radiation rather than absorb it (Fay, Aerospace Technologist, Chemical Engineer, Researcher, 2012) (Fay, Thibeault, & Earle, 2012). Also a collaboration among Los Alamos National Laboratory, Lawrence Livermore National Laboratory, and Virginia Tech has been examining nanofoams for the same purpose (Fu, et al., 2012).

3.8.7 Potential Nanotechnology Applications for Isotopic Enrichment

Strategies for employing nanotechnologies for isotopic enrichment involve exploitation of kinematic recoil or molecular tethering to exaggerate mass differences to the point that principles of mass spectrometry (D. Wells, personal communication, 2014) can replace traditional methods. Enrichment of fissile materials using kinetic recoil is of little practical value, because of the inertial mass of the atom versus the kinetic energy of the expelled particle. Furthermore, neutron decay of either U-238 or U-235 doesn't yield any fissile product, so it's essentially pointless. However, separation of Mo-99 from Mo-100 by neutron decay is potentially a very useful mechanism for achieving the higher specific activity that could make electron linear accelerators economically competitive (S. Winston, personal communication, 2014).

3.8.8 Potential Nanotechnology Applications for Ore Beneficiation and Purfication

Though estimates of practically exploitable fissile material resources to fuel reactors clearly depend on international policies on nonproliferation, there are literally tons of uranium suspended in seawater ("The Sea," 2012). The same is also true for gold and platinum, but in all cases there currently is huge economic

barrier for extracting these. That might possibly change with developments like those reported by Chris Janke of Oak Ridge National Laboratory and his collaborators regarding high capacity nanostructured mats that exceed the separations efficacy of conventional methods by two to three orders of magnitude ("ORNL technology,"2012).

Chapter 4: Conclusions and Recommendations

4.1 Conclusions

In researching this thesis I was amused by a quotation from a nuclear industry expert ("Nanotechnology," n.d.) to the effect that since sintering of nuclear fuel has always involved reducing the uranium oxide to a powder with particle size distribution less than 100 nm, the nuclear industry could claim to be the "father of nanotechnology". The irony of this is that I had just previously reviewed an article by another nuclear expert (Drexler, 2009) asserting that nanotechnology has no applicability to nuclear issues in any way.

Clearly nanotechnology is not only relevant to addressing the challenge of nuclear science, but is directly relevant to almost every conceivable aspect. Direct manufacturing on the nano and molecular scale has potential value in manipulating material structures at their most fundamental level to make targets for accelerators and fuel pellets for reactors. Engineered grain boundaries might become a standard feature of nuclear fuel along with radial conduits for heat transfer or possibly engineered voids for collection of gaseous fission products (Winston & Marshall, 2012).

There are two basic premises of this thesis: 1) nanotechnology can be meaningfully utilized to address nuclear challenges and 2) research in the intersection of nano and nuclear (nanonuclear) could be far more effective if conceived, conducted, and funded within a coherent framework. A portion of the widespread evidence to support both contentions was summarized indicating that not only are there numerous parallel, disconnected inquiries moving forward in the various research institutions in the US but many more similar studies are proceeding abroad. Yet there remains no dedicated, regular forum in which ideas and results can be exchanged, there are no publications that regularly summarize and publish research, and there is no primary clearinghouse to coordinate efforts.

4.2 Recommendations

My overall effort with this thesis has been to update and extend the results and conclusions from the workshops in which I participated in 2010 and 2012. We planned and conducted the 2012 workshop to meet the following objectives:

1.) Identify specific areas of nuclear energy research most amenable to nano enhancements
2.) Define functional requirements and performance criteria that nano adaptations must meet in specific nuclear applications, and
3.) Describe plausible testing sequences that will yield the performance data needed to ascertain the suitability of nanomaterials in nuclear applications. (Winston & Marshall, 2012)

With the input of the participating nano and nuclear technology experts we succeeded in meeting those objectives. We organized the workshop and reported the results in five broad categories: 1. Chemical; 2. Mechanical; 3. Physics; 4. Thermal hydraulics; 5. Nanoscale modeling. I won't try to summarize all the input here; rather, I will address a few of the major conclusions we drew in preparing the workshop report.
At the time we issued the 2012 workshop report, we concluded, "Although nanonuclear research could proceed along its current ad hoc lines there are substantive fundamental knowledge gaps that may be more effectively addressed by a cohesive, coordinated national initiative" (p. 3).

From my investigation related to this this project, I conclude that little has changed in the past two years. Nanonuclear research continues on an ad hoc basis; there has been little or no effort to establish a cohesive, coordinated national initiative.

Among participating federal agencies the Department of Energy (DOE) has invested heavily in nanotechnology R & D through the National Nanotechnology Initiative (NNI). DOE investments from 2006 through 2014 have totaled $369.59 M with the greatest of those in Nanotechnology Fundamental Phenomenon and Processes ($126.4 M), Nanomaterials ($107M) and Major Research Facilities & Instrument Acquisition

($110M). Of the sixteen federal agencies participating in NNI, DOE's total investment is the third largest—less only than the National Institutes of Health ($460.8) and National Science Foundation ($430.9) (nano-dashboard. Nano.gov 4/2/14). Of the DOE sub-organizations the Office of Science appears to be the largest investor. In the NNI's 2015 budget supplement, I could find no mention of nanotechnology R & D targeting nuclear energy needs, nor could I find any investment attributed to DOE Nuclear Energy (NE) Programs (National Nanotechnology Initative Investments, 2014).

My review of the DOE-NE FY-2015 budget submittal produced similar results—only scattered mentions of funding for nanotechnology R &D. For example the Nuclear Fuel Cycle Program mentions the exploration of nanomaterials as highly efficient sorbents to harvest dilute uranium from seawater (U.S. Department of Energy, 2014). The 2014 DOE Nuclear Energy Program call for proposals, contains only one allusion to nanotechnology—advanced cooling materials were mentioned as an example of a potential nanotechnology application (U.S. Department of Energy, Nuclear Energy Programs, 2013).

Since many nanonuclear technology applications would require review and approval by the U.S. Nuclear Regulatory Commission (NRC) or an NRC Agreement State, I investigated that agency's involvement with nanotechnology research. I could find no evidence that NRC has actively engaged in such research and the agency is not identified as an investor in the NNI through budget year 2015. In response to questions from their advisory committees, NRC managers and staff have described the agency's role in nanotechnology as monitoring developments that might be applied within the nuclear industry, assuming these would occur well into the future (Macfarlane, 2012).

I recognize that there are probably on-going nanonuclear R & D efforts that I haven't found in my review of the entities most likely to be engaging in such, including those in other countries. However, I believe any others identified would not refute my conclusion that nanonuclear research continues on an ad hoc basis with little or no effort to coordinate R&D aimed at meeting nuclear energy needs.

In the overall scheme of things, the Department of Energy—logically Nuclear Energy Programs—would

be the entity most likely to undertake such a coordination effort. Presently, it appears that the NE Program is emphasizing three major, coordinated R & D efforts, which they identify as potentially high impact: advanced adsorbent material for extracting uranium from seawater; the advanced Supercritical Carbon Dioxide (SCO2) Brayton cycle energy conversion technology; and advanced small modular reactors (U.S. Department of Energy, 2014). Significant funding over several future budget cycles would likely be required to establish the kind of momentum for nanonuclear R &D that these initiatives have achieved.

However, our workshop participants reached another significant conclusion, which I adopt as the principal recommendation for continuing R&D in nanonuclear technology. According to our participants "There aren't yet enough reliable data regarding performance of nanostructured materials subjected to high radiation environments to form meaningful conclusions" (Winston & Marshall, 2012, p. 4). Our report went on to say, "…a general consensus was that the first step in assessing any benefits that nanoscience might offer, is to conduct substantive irradiation studies of materials and methods (p. 4).

Therefore, my primary recommendation is that the research on nanomaterials for nuclear technology applications be focused in scope on nanomaterial behavior in high radiation environments. In those cases where our workshop participants recommended projects within this scope, they also identified each one via a metric entitled "Experimental Readiness Level" or "ERL" (p. 4). They based this metric on criteria such as: complexity of the experiment; availability of an irradiation source to elucidate effects; relative value of the result to addressing high priority nuclear technology challenges; and the difficulty of performing meaningful post irradiation examinations.

The Chemical Working Group summed up the basic issue best in their input to our report, "An overriding question pertinent to all potential in-core applications of nanomaterials in a high flux, high temperature environment is simple survival" (p. 5). If we consider this focused scope of research on nanomaterials in the context of the entire host of research that is—or could be--conducted, survivability becomes the first gate (go-no go) in a technology development process (Cooper, 1990, pp. 44-54). Nanomaterials under consid-

eration for nuclear technology applications must first pass the test of survivability, and the preservation of their desirable properties for their intended applications. A well-designed and conducted research program focused on the effects of irradiation on nanomaterials would function as the initial screening to categorize nanomaterials as go or no-go for further study. This would allow a broader research program to follow, and keep precious research dollars focused on those nanotechnologies that pass the screen. The ability to predict in-core and in-facility nanomaterial performance over facility lifetimes will be a prerequisite world-wide to satisfy the requirements of various nuclear industry oversight agencies in their licensing reviews. The collection of existing data- and production of new data—now will help facilitate the oversight review and approval process when the time does come.

A reasonable follow-on question might be who would propose and conduct such research? I recommend that the Idaho National Laboratory (INL) propose the research for funding by the DOE Office of Nuclear Energy. The INL is after all the Nation's Lead Laboratory for Nuclear Energy, and it houses and operates the Advanced Test Reactor (ATR), which is designed to supply tailored fluxes for experiments in a variety of configurations. Apparently, ATR has already been put to use for irradiating nanomaterials, and INL personnel have been involved in the testing. One recent study investigating radiation defects and grain size in low carbon steel (Alsabbagh, et al., 2013, pp 302-310) acknowledges the assistance of INL personnel at the Center for Advanced Energy Studies (CAES). That 2013 report discusses a follow-up study underway at the time using the ATR for nanomaterial sample irradiation.

I suggest that INL fund a one-year effort by a nuclear technology subject matter expert (SME) in collaboration with a nanotechnology SME to prepare a proposal for funding to be submitted to DOE Nuclear Energy Programs for inclusion in the FY-2016 budget cycle. The scope of their activities could involve updating in greater technical detail, and validating, the R&D projects identified as high ERL in our 2012 report. Their preparation should also involve an extensive review of the literature reporting irradiation experiments with nanomaterials. Andrievski (Andrievski, 2011, pp. 54-67) published a literature review of such experimental work; while probably not exhaustive his reference list contained 71 published works. However, he noted

that "…the study of the radiation defects in nanomaterials is still in its infancy" (p. 55).

The SMEs could consult with the pool of nuclear and nanonuclear participants in our workshop to refine and apply the ERL criteria to the broader base of published work, with the goal of developing a short list of the most pertinent and valuable experimental work, and the order in which it should be conducted. These data would then be used as input to a proposal for funding.

The application of the ERL criteria would take into account constraints such as the availability and suitability of the ATR (or another facility) for irradiation services, and the availability and suitability of post-irradiation examination facilities. Available funding for a future budget cycle is an uncertain constraint at the present time. However, the application of the ERL should provide a sense of priority for the proposed work, which would allow the proposers to adjust proposed work to fit within the constraints of available funding.
In my follow-up discussions with our workshop participants, I found continued optimism on the part of many for the potential application of nanomaterials and processes to the continued development of nuclear technology. For the most part, they have been disappointed that a cohesive, coordinated national initiative has not come about. However, they stand ready to continue contributing to such an effort.

I began my work on this thesis with the idea that I could create and recommend a complete pathway to that cohesive, coordinated national R&D effort in nanonuclear technology. My reconsideration of the results of the very report I helped author, along with my follow-up discussions with the other contributors, helped me to see that the overall goal is not attainable without that vital first step—the investigation of nanomaterial survivability in the harsh nuclear environment. With that understanding we can work our way out from the core to find efficient and effective nanotechnology applications in nuclear systems. During my thesis research proposal meeting, one of my committee members said he believes a master's thesis should report "a problem well-solved". I admit that I have not solved the problem of nano and nuclear technology integration, but I hope I have been able to recommend a rational and reasonable first step toward solving the problem.

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Appendix A

Interview Question/Answer Matrix

Appendix A

Interview Question/Answer Matrix

		Los Alamos National Laboratory	Oak Ridge National Laboratory	Rice University (1)	Rice University (2)
1	**Is your research focused primarily on nanotechnology or nuclear?**	Nuclear/Nano	Nuclear/Nano	Nano	Nano
2	**What is your major research focus?**	Oxide Dispersion Strengthened metals	Use of nano inclusions for enhancing mechanical properties of materials	Nano reporters and graphene applications	Transition interfaces and boundary layer effects
3	**How long have you been working on this particular issue?**	Since 2008	Since 2010	18 years	12 years
4	**What is your source of funding?**	FCRD	LDRD	Grants	industry
5	**Within your traditional research community do find acceptance or resistance to exploring applications of (nano or nuclear, depending on researcher)?**	Always encounter some resistance to new ideas. Generally accepted	A bit of both;encounter some skeptical views	We can't have any radioactive materials in any of our labs.	Never tried anything that somebody somewhere didn't like. I welcome the challenge
6	**When you interface with (experts from the other field--nano or nuclear) do you encounter any reservations either explicit or implied?**	Not at all	Sometimes. Some nano experts are openly anti-nuke	I've run into nukes who regard nano as a passing fad.	I don't pay any attention to them
7	**Do you feel that there are adequate standards and regulations to cover the development of nanonuclear in general?**	Don't really know--fear over-reaction from regulators	Nuclear is already over-regulated. Don't think there's any room to get crazier.	I don't know about nuclear regulations. The lay fears regarding nano are largely hype and nonsense	We shouldn't start looking for restrictions until we know the consequences.
8	**Are you aware of specific initiatives besides what you are doing to explore the intersection of nanotechnolgy and nuclear sciences.**	I'm more aware since the workshops but it's still hit or miss	Know what's going on at the other National Labs but don't have a clue what industry is up to	The Houston workshop was the first time I'd ever thought about nuclear applications	I'm really intrigued and am finding more and more possibilities the more I learn about nuclear.
9	**Do you see your work as having applications in adjacent fields?**	Very, definitely	Maybe, I don't really think there are a lot of regular industrial applications that are as severe as this	Actually my work in other applications is most likely to be useful in nuclear	It always has, but that's probably because I'm always looking for possibilities
10	**Do you see value in expanding the level of inquiry along these lines?**	The value at the scientific level is obvious but it's not understood at the funding level	Of course. But bear in mind that I have a vested interest in seeing this gain more support	I don't know--hadn't thought much about nuclear either way. Seems like a good idea.	I think it's potentially revolutionary

		Los Alamos National Laboratory	Oak Ridge National Laboratory	Rice University (1)	Rice University (2)
11	**Are there areas of nanonuclear research that you feel should be given more attention?**	Fuel fabrication and heat transfer	Agents for sequestering fission products	Isolating radioactive waste	
12	**Did you participate in any of the nanonuclear workshops?**	Yes, all 3	The last 2	Houston	Just the one in Houston in 2012
13	**Do you think more organized exchanges (e.g. more workshops, seminars, consortia, conferences) would have value?**	Absolutely but nobody seems to be taking this up	Yes, but we need to have some research findings to report. We can't just keep talking about what we might do or the benefits we might see. We have to do some real research	Definitely, nanoscientists don't have much opportunity to learn about nuclear and it is so complex that a 3-day conference just scratches the surface, need something more substantive	We ought to get some research done first don't you think? I sent two proposals to DOE and both were rejected as "too speculative"
14	**Would you say that you have a fairly comprehensive working knowledge of other work similar to yours or that might be complementary to yours?**	I know just about everybody who's worked on ODS in this industry but outside of the Labs, no	I'd like to think so, but the world of nanotechnology is pretty opaque from an nuclear lab perspective	In my field yes. As might apply to nuclear, I haven't a clue if anybody is doing similar work	Very much so
15	**Are you aware of work in adjacent fields that is similar to your work?**	To a degree, the literature is pretty well populated in material science aspects of ODS	No not really. I follow stuff that directly pertains whereever I can find it but that's a very narrow lens.	Applied to nuclear? No.	I'm not sure what "field" I'm supposedly confined within. The world is my oyster and all opportunities to apply what I know are fun
16	**Do you feel you have enough access to information in adjacent fields to stay well informed on possible adaptations to your line of inquiry?**	I've got access to more info than I can digest right now but most of it is pretty narrowly confined within the discipline. It would be interesting to see what's happening in other comparable applications.	Frankly, I don't have enough expertise in the other disciplines to have a full appreciation of the possibilities.	Within my area of research and its application. Until somebody decides to put some research money into nanonuclear, I don't know any nanoscientists who feel the impulse to deal with the nuclear headaches.	You can never have too much info. Especially when it comes down to getting funding.

		Massachusetts Institute of Technology (1)	Massachusetts Institute of Technology (2)	Lockheed Martin (1)	Lockheed Martin (2)
1	**Is your research focused primarily on nanotechnology or nuclear?**	Nuclear	Nano/Nuclear	Nano	
2	**What is your major research focus?**	Thermal hydraulics	Grain boundary effects and microstructural characteristics	Nano electronics	Thorium fuel cycle
3	**How long have you been working on this particular issue?**	5 years	3 years	9 years	2 years
4	**What is your source of funding?**	DOE	Grants	IRAD	IRAD
5	**Within your traditional research community do find acceptance or resistance to exploring applications of (nano or nuclear, depending on researcher)?**	Acceptance generally	Acceptance	There are a lot of nuke haters out there--I'm not one of them.	Acceptance
6	**When you interface with (experts from the other field--nano or nuclear) do you encounter any reservations either explicit or implied?**	No	Sometimes	Sure, once in a while but you can't let that dictate where you go or what you do	I don't perceive any reservations
7	**Do you feel that there are adequate standards and regulations to cover the development of nanonuclear in general?**	Standards and regulations, if necessary, should evolve to address real issues not paranoia.	Probably better to develop a cautious approach than to find out after the fact that we've made a big mess of things. I like the precautionary principle with a grain of salt.	I'm on two international standards committees on nano. EPA keeps publishing studies but they don't have a clue what to do.	Probably. It's one of those things that someone should be thinking about as we go along.
8	**Are you aware of specific initiatives besides what you are doing to explore the intersection of nanotechnolgy and nuclear sciences.**	Yes I have numerous opportunities to share info with colleagues and collaborators	Not nearly as much as I'd like. It's really hard to follow. DOE Office of Science is funding some stuff but I generally work with NE.	I am now, but I hadn't really looked at it before 2010	These were more evident when I was in grad school--it's less obvious in an airplane company research portfolio
9	**Do you see your work as having applications in adjacent fields?**	Depends upon what you mean by "adjacent". If you mean nuclear medicine, yes. If you mean nuclear weapons, no.	It certainly does	Obviously it does. Everybody needs stronger lighter stuff that lasts longer. Nuke is just tougher on everything than any other thing.	That's one thing that does show up regularly in my line of work
10	**Do you see value in expanding the level of inquiry along these lines?**	I'd have some reservations about who was undertaking this work and why they were doing it.	We need funding so we can launch some real research. We're just working the fringes here.	Somehow the case has to be made to put some funding in this bucket. Nuke is on its back so the vendors are pretty stingy with their money right now and DOE is playing it pretty close. It's up to Congress to decide if this is something they can get behind.	It's hard to say at this point what the constraints might be. The field looks wide open, but there doesn't seem to be enough of a common thread running through it.

		Massachusetts Institute of Technology (1)	Massachusetts Institute of Technology (2)	Lockheed Martin (1)	Lockheed Martin (2)
11	**Are there areas of nanonuclear research that you feel should be given more attention?**	Phonon transport without a doubt.	Thermal conductivity	Fuel cladding	The whole accident tolerant fuel issue
12	**Did you participate in any of the nanonuclear workshops?**	No	No	Yes, I helped organized them	No
13	**Do you think more organized exchanges (e.g. more workshops, seminars, consortia, conferences) would have value?**	I'm not sure. I talk to most of the people already involved in this work all the time. I don't know if I'd have the time for more.	Well I'm giving a paper at the upcoming TechConnect Meeting but I don't know if there are any other venues on this topic	I'm co-chairing a session at TechConnect in June but after that the calendar is really empty. Yes, I think we need something to build and sustain momentum	If this is going to go anywhere there's got to be some regular vehicle for cross fertilization. I don't see it right now.
14	**Would you say that you have a fairly comprehensive working knowledge of other work similar to yours or that might be complementary to yours?**	I'd say I'm the leading expert in the field	No. I know a lot about my subject but I don't have a reliable way to keep track of who is doing what in this area outside of my discipline	I would, mainly because of my position at Lockheed Martin. I oversee all the research and that covers an awful lot of ground.	Not nearly as current as I'd like to be.
15	**Are you aware of work in adjacent fields that is similar to your work?**	Yes	Not as much as I'd like. It's hard to cover the whole span of nuclear research and that of nano research and find the commonalities.	To some degree. The respective fields are way too big for any single individual to track	Some of it. It would be nice if there was some type of overall organization.
16	**Do you feel you have enough access to information in adjacent fields to stay well informed on possible adaptations to your line of inquiry?**	I generate the information of importance in this field.	This whole area is really new and the number of active practitioners who are engaged in it on a daily basis are very limited	Access to reliable information? No. I get enough unsubstantiated stuff every day to fill up my inbox but good info is hard to find.	No. It pretty much boils down to what I can glean on my own.

		University of Florida	Brookhaven National Laboratory	Texas A&M University	Sandia National Laboratory
1	**Is your research focused primarily on nanotechnology or nuclear?**	Nano/Nuclear	Nuclear	Nucelar/Nano	Nano/Nuclear
2	**What is your major research focus?**	Nuclear fuel	Nuclear fuel	Nuclear fuel	Synthetic zeolite absorbers
3	**How long have you been working on this particular issue?**	42 years	35 years	22 years	13 years
4	**What is your source of funding?**	FCRD	FCRD	FCRD	FCRD
5	**Within your traditional research community do find acceptance or resistance to exploring applications of (nano or nuclear, depending on researcher)?**	Don't really care	Acceptance	Acceptance	Some skepticism
6	**When you interface with (experts from the other field--nano or nuclear) do you encounter any reservations either explicit or implied?**	Some degree of reservation is appropriate	Good science is always leavened with a degree of caution	Sometimes run into skepticism but I wouldn't call it opposition	Alot of the time the initial reaction is negative, but when you explain what you're working on and how it applies that usually goes away
7	**Do you feel that there are adequate standards and regulations to cover the development of nanonuclear in general?**	Yes	We probably won't know the answer to that unless something bad happens	That's hard to tell. Unwarranted regulation can seriously hamper the lines of research that can be pursued without good reason. The other side of the coin is too little and somebody or something gets hurt. There has to be a balance of caution and imagination	I don't know what the considerations are. Does anyone have enough information at this stage to answer that?
8	**Are you aware of specific initiatives besides what you are doing to explore the intersection of nanotechnolgy and nuclear sciences.**	Within the nuclear R&D community for sure	Hadn't had the opportunity to think about it very much before the Gaithersburg workshop	To a limited degree yes. It would be helpful if there were more avenues for more information exchange	I'm aware of some similar work--that's where I get ideas sometimes. But there's a lot of work going on that I'm vaguely aware of that is difficult to decipher
9	**Do you see your work as having applications in adjacent fields?**	Not really. The only thing nuclear fuel is good for is running a nuclear reactor.	I suppose that's possible. What we learn in one area at the fundamental level is bound to be relevant to another problem in another area	It does. My grad students often find employment in adjacent areas.	Most of my work is derivative from adjacent fields so it extends both ways.
10	**Do you see value in expanding the level of inquiry along these lines?**	Some of these ideas have merit; I'm not so sure about all of them.	I see a lot of value in it. Discoveries hinge on having a good idea where to look and having a whole bunch of people looking. We don't have enough people looking in the right places yet.	I definitely think that more work should be done but I don't think there's any funding for it	I would like to see more work initiated because there seems to be a lot of potential value and unexplored territory. I just don't know where the funding would come from. There isn't enough as it is.

		University of Florida	Brookhaven National Laboratory	Texas A&M University	Sandia National Laboratory
11	**Are there areas of nanonuclear research that you feel should be given more attention?**	Heat conduction inside nuclear fuel	The whole nuclear fuel cycle warrants some thoughtful rethinking with nano in mind	Of course my focus on nuclear fuel leads me to our problems: fission product gettering, heat transfer, swelling, fretting, creep, corrosion	I'm not aware of any part of the nuclear fuel cycle that wouldn't realize benefit from looking beyond the traditional lines of inquiry.
12	**Did you participate in any of the nanonuclear workshops?**	The one in Gaithersburg	Yes, the last one	Houston and Gaithersburg	Gaithersburg
13	**Do you think more organized exchanges (e.g. more workshops, seminars, consortia, conferences) would have value?**	The FCRD team meets at least once a year and I usually attend that	Definitely. The more opportunities there are to share information and knowledge first hand with one another, the faster this will expand	All of them would help. A seminar series would go a long ways toward building a knowledgeable base from which more ideas could be developed.	In the early stages of any research effort, the more opportunities there are to learn from one another the better. It doesn't seem like there's been any focused effort since the Gaithersburg meeting.
14	**Would you say that you have a fairly comprehensive working knowledge of other work similar to yours or that might be complementary to yours?**	I don't know if I would call it "comprehensive" knowledge. I'm aware of some other work.	It's admittedly limited. I wish I knew more researchers in nano. We just don't travel in the same circles.	More would be better. It's hard to know what some of the papers are about because they're so focused on technical aspects of another discipline that I'm not an expert in.	It's pretty limited to what I have the time to dig into. I wish I had more time or some way to get distilled synopses of related work.
15	**Are you aware of work in adjacent fields that is similar to your work?**	I'm not sure what "an adjacent field" might be. I'd be interested, that's for certain.	To some extent. That's the benefit of a long career at a National Lab	I don't think we have enough shared understanding of the problems we're trying to address. We need more basic information exchange	To some extent, but that's limited by how much time you can dedicate to curiosity
16	**Do you feel you have enough access to information in adjacent fields to stay well informed on possible adaptations to your line of inquiry?**	No. There's no dedicated body of literature. The nano publications all are focused on electronics or biology	It would help a lot if there was some way of getting more related focus. There is so much work going on in nano that you can't keep up with it all and even then, a lot of it is so narrowly focused on a special application that it's hard to figure out what they experts are talking about	Well, like I said earlier, it's sometimes hard for experts in one field to know enough about the key issues in another to recognize related opportunities. There needs to be some way to bridge that gap	More frequent meetings between nano and nuclear researchers would be very valuable.

		Argon National Laboratory	Idaho National Laboratory	National Institute for Nanotechnology	University of Notre Dame
1	**Is your research focused primarily on nanotechnology or nuclear?**	Nucelar	Nuclear	Nano	Nano
2	**What is your major research focus?**	Advanced reactor concepts	irradiation effects in materials	Synthetic zeolite getters	Uranium fullerenes
3	**How long have you been working on this particular issue?**	23 years	12 years	Since 2005	Since 2009
4	**What is your source of funding?**	NE	FCRD	Federal Grants	Office of Science
5	**Within your traditional research community do find acceptance or resistance to exploring applications of (nano or nuclear, depending on researcher)?**	Not really resistance, just questioning	I'm a bit skeptical myself	Most researchers are pretty open minded by nature	Some resistance
6	**When you interface with (experts from the other field--nano or nuclear) do you encounter any reservations either explicit or implied?**	No reservations that I see	Usually at least some degree of reservation	I haven't observed any real reticence	It's hard to tell sometimes. I'd say no.
7	**Do you feel that there are adequate standards and regulations to cover the development of nanonuclear in general?**	I hadn't really thought about it as a separate distinct set of rules. It seems that the nuclear rules are pretty conservative already. I'm not sure what adding more precautions for nano would gain	That may be premature	Not sure what's not already covered.	It makes sense to give it some thought before we get too far down the road.
8	**Are you aware of specific initiatives besides what you are doing to explore the intersection of nanotechnolgy and nuclear sciences.**	I keep track of progress in a lot of different fields because I'm always looking for things that can be adapted and adopted in our area.	I think so. I try to stay on top of relevant developments in my field	Kind of hard to know what you don't know don't you think?	I work on the basic science side of things and although I'm generally aware of challenges in nuclear, it's refreshing to have direct interaction with the people who are trying to solve the day to day problems.
9	**Do you see your work as having applications in adjacent fields?**	With certain limitations of course but generally speaking yes.	I hope so. One tries to keep the broader perspective in mind.	Most of my work is for other applications to begin with so there's no doubt about its applicability in other areas.	I'd like to think that it does
10	**Do you see value in expanding the level of inquiry along these lines?**	I see lots of opportunities for starting new research; I just don't know how you'd attract the money.	There's a lot of work going on right now in my area, but there's always room for more. It's a question of priorities.	Generally this line of inquiry begins in other fields. There hasn't been a lot of direct funding for this work by the nuclear establishment that I'm aware of	We've only just scratched the surface on the potential value of this work. Where it goes from here will depend on the word getting out to potential users.

		Argon National Laboratory	Idaho National Laboratory	National Institute for Nanotechnology	University of Notre Dame
11	**Are there areas of nanonuclear research that you feel should be given more attention?**	There are some pretty novel reactor concepts that nano might really give a boost.	I'm not sure if nano is the answer.	Fission product management is a big challenge from the reactor through to the end of the fuel cycle.	I don't know what the priorities should be but it appears to be singularly promising on all fronts. It's disappointing that there isn't a greater awareness of the potential.
12	**Did you participate in any of the nanonuclear workshops?**	No	The first one	No	The Gaithersburg one
13	**Do you think more organized exchanges (e.g. more workshops, seminars, consortia, conferences) would have value?**	I'd like to see more seminars on the subject.	Do you mean more organized meetings or additional meetings? Better organization of the ones we have would be good.	I'd like to have more opportunity to get engaged in such discussions	More would be definitely better.
14	**Would you say that you have a fairly comprehensive working knowledge of other work similar to yours or that might be complementary to yours?**	I think it's fair to say that I keep up on the stuff that's immediately relevant but there's probably a whole lot that might have value that is a couple of degrees further removed that would be interesting	I keep up with what's happening.	Not enough	As far as practical applications go I'd have to say no. There's not enough opportunity to share concepts and progress between the science side and the engineering side
15	**Are you aware of work in adjacent fields that is similar to your work?**	Yes, some of it is accessible and obvious. However, there are far more papers than I have time to peruse	Most of it.	Not in the nuclear application. There isn't enough dialogue	There is clearly more work going on in the adjacent fields than in this particular area.
16	**Do you feel you have enough access to information in adjacent fields to stay well informed on possible adaptations to your line of inquiry?**	It would be nice to have an assistant who could be my sentinel looking out for every possibility.	Access to information isn't the problem. It's getting enough funding to do the work that we already have.	No, there needs to be a forum for stimulating cross fertilization	It would certainly help if there was some type of standing information exchange. This haphazard approach is pretty hard to plan anything around.