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Research, Development and Demonstration (RD&D) Needs for Light Water Reactor (LWR) Technologies

A Report to the Reactor Technology Subcommittee of the Nuclear Energy Advisory Committee (NEAC) Office of Nuclear Energy U.S. Department of Energy

LWR RD&D Working Group

April 2016

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LWR RD&D Working Group
Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

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MESSAGE FROM THE CHAIRPERSONS

Light Water Reactor (LWR) technology, the dominant reactor technology today and an essential element of the nation's energy supply, is facing a variety of challenges. To meet these evolving challenges, and to enable nuclear energy to achieve its full potential in enhancing the nation's energy security and in reducing U.S. and global carbon emissions, the Department of Energy (DOE), in collaboration with industry and other stakeholders, has examined its Research, Development and Deployment (RD&D) portfolio to identify and prioritize additional activities that should be undertaken in support of existing and future LWRs. This report is the result of this examination.

The DOE Office of Nuclear Energy (DOE-NE)'s Office of Light Water Reactor Technology (NE-72) engaged a Working Group of 14 Subject Matter Experts from industry, national laboratories, academia and regulators to develop RD&D inputs. The Working Group established a list of RD&D needs for consideration by DOE and then ranked them in a structured prioritization process.

The Working Group held three face-to-face meetings, plus three webcast meetings between July 2015 and February 2016. Inputs were solicited from various nuclear energy experts and energy experts broadly from industry, academia, national laboratories, Federal and state regulators, Congressional staff, professional nuclear societies and environmental organizations. A total of 35 experts provided inputs to the Working Group at these meetings.

The purpose of this document is to lay out proposed actions for LWR RD&D activities over the next ten years (the period 2018 -2028). This report not only encompasses current program areas but also explores activities that are beyond the current programs for the longer term.

The Working Group established a detailed list of RD&D needs or recommendations for consideration by DOE. This information was developed without regard to whether the RD&D was already underway or for which organization(s) (i.e. DOE, EPRI nuclear industry, etc.) are or would be responsible for execution. In the discussions, the Working Group recognized that a good deal of the RD&D on these issues was already underway. However, the Working Group felt it was important to develop a comprehensive list for consideration. DOE will work collaboratively with EPRI and industry to determine whether existing RD&D should be expanded as well as which organization should address the RD&D needs not currently underway.

The Working Group appreciates the opportunity to provide this critical input to DOE as well as the outstanding support provided by the DOE and the Idaho National Laboratory staff. The process undertaken by the Working Group was thorough and rigorous, and resulted in important and timely recommendations for DOE. The Working Group concluded that strong support to LWR technology RD&D should be a national priority.

Kathryn A. McCarthy

Director, Technical Integration Office
Light Water Reactor Sustainability Program
Idaho National Laboratory

Bradley J. Adams

Vice President, Engineering
Southern Nuclear Operating Company

CONTENTS

ACRONYMS

ALARA	as low as reasonably achievable
ALWR	advanced light water reactor
ANL	Argonne National Laboratory
BOP	Balance of Plant
BRC	Blue Ribbon Commission
BWRs	Boiling Water Reactors
CAPEX	Capital Expenditure
CASL	Consortium for Advanced Simulation of Light Water Reactors
COL	Combined Operating License
D&D	decontamination and decommissioning
DC	Design Certification
DMLS	Direct Metal Laser Sintering
DOD	Department of Defense
DOE	Department of Energy
DOE-NE	DOE Office of Nuclear Energy
EPRI	Electric Power Research Institute
ESP	Early Site Permit
EU	engineering unit
FERC	Federal Energy Regulatory Commission (DOE)
FOAKE	First-of-a-Kind Engineering
GEN III	Generation III Reactor
GPS	Global Positioning System
HFE	Human Factors Engineering
HIP	Hot Isostatic Processing
HRA	Human Reliability Analysis
HSI	Human System Interface
I&C	Instrumentation and Control
IEEE	Institute of Electrical and Electronics Engineers
INL	Idaho National Laboratory
INPO	Institute for Nuclear Power Operations
IRP	integrated mapping

ITAACs	Inspection, Test, Analyses, and Acceptance Criteria
LANL	Los Alamos National Laboratory
LBLOCA	large break loss-of-coolant accident
LNT	linear non-threshold
LLW	Low-Level Waste
LNT	Linear No-Threshold
LOCA	loss-of-coolant accident
LWR	Light Water Reactor
LWRS	Light Water Reactor s Stainability
M&O	maintenance and operations
M&S	materials and supplies
MIT	Massachusetts Institute of Technology
Moose	Multiphysics Object Oriented Simulation Environment
NDE	Non-Destructive Examination
NDT	nondestructive testing
NE	Nuclear Energy
NE-72	Office of Light Water Reactor Technology
NEAC	Nuclear Energy Advisory Committee
NEI	Nuclear Energy Institute
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission
NRC-RES	Nuclear Regulatory Commission Office of Research
O&M	Operations and Maintenance
OPEX	operating expense
ORNL	Oak Ridge National Laboratory
OSHA	Occupational Safety and Health Act
OTSGs	once-through steam generator
PIE	Post-irradiation examination
PMs	performance monitor
PRA	Probabilistic Risk Assessment
PWRs	Pressurized Water Reactors
R&D	research and development
RCIC	reactor core isolation cooling

RCS	Reactor Cooling System
RD&D	Research, Development and Deployment
RD&D	Research, Development and Demonstration
RFI	Requests for Information
RI	Risk-Informed
RISMC	Risk-Informed Safety Margin Characterization
RPV	Reactor Pressure Vessel
SC	Steel plate and concrete composites
SME	subject matter experts
SMR	Small Modular Reactor
SSC	Systems, Structures, and Components
TDS	total dissolved solids
T-H	thermal-hydraulic
U.S.	United States
UNF	Used Nuclear Fuel
VRLA	Valve-Regulated Lead Acid
WG	Working Group

Research, Development and Demonstration (RD&D) Needs for Light Water Reactor (LWR) Technologies

1. INTRODUCTION

Nuclear energy is an essential source of clean, safe, and reliable electricity, both in the U.S. and around the world. The 99 nuclear energy plants in the U.S. provide about 20% of the nation's electricity and over 60% of our carbon-free electricity. The U.S. fleet of nuclear energy plants set a new all-time record of reliable performance in 2015, with an average capacity factor of 91.9%. What this means in practical terms is that nuclear energy is <u>the most reliable source of baseload non-emitting electricity in the U.S.</u>

> *"Nuclear energy is currently our largest source of carbon-free electricity. DOE will continue to pursue advancements in nuclear energy technologies to simultaneously support the Administration's "all of the above" strategy and the need to limit greenhouse gas emissions."*
>
> DOE Strategic Plan, March 2014

<u>Nuclear energy is essential to achieving the nation's clean air and climate change mitigation goals.</u> As the major source of carbon-free electricity in the U.S., it has the added advantage of being a dispatchable source of electricity. Renewable energy sources, such as wind, solar, and geothermal, are also important sources of carbon-free electricity, but because of their intermittency and geographical limitations, they are not dispatchable and thus, cannot address U.S. environmental goals on their own, absent dramatic breakthroughs in energy storage technology and economics. Both the President's Climate Action Plan and the U.S. response to the COP-21 agreement in Paris in December 2015 rely heavily on nuclear energy.

The White House held a Nuclear Energy Summit on November 6, 2015, that recognized, among other nuclear energy initiatives, the establishment "… of a Light Water Reactor (LWR) Research, Development, and Deployment Working Group: DOE is formally announcing the establishment of the LWR Research, Development, and Deployment (RD&D) Working Group to examine possible needs for future RD&D to support the development of competitive advanced LWRs, as well as maintain the safe, efficient operations of currently operating nuclear power plants. The group will consist of federal, national laboratory, and industry participants…"

> *"As detailed in the Climate Action Plan, President Obama is committed to using every appropriate tool to combat climate change. Nuclear power, which in 2014 generated about 60 percent of carbon-free electricity in the United States, continues to play a major role in efforts to reduce carbon emissions from the power sector."*
>
> White House Press Release, Nov. 6, 2015

This report is the result of this initiative.

Light Water Reactor (LWR) technologies, comprised of Pressurized Water Reactors (PWRs) and Boiling Water Reactors (BWRs), are the primary nuclear technology available today that is capable of addressing the nation's clean air and climate change mitigation goals. LWR technologies are proven, safe, reliable, and economic. They are the focus of this report.

The nuclear energy industry is faced with a number of challenges today, including low natural gas prices, and various adverse market conditions. These challenges are discussed in more detail in Section 3. Although many of these challenges are largely policy-related or regulatory-related, technological innovation can be instrumental in providing solutions to these challenges, as well as providing opportunities to improve the economics of current and new nuclear plants.

1.1 Federal Investment in LWR Technology

While industry is likely to invest in applied research programs that are directed toward enhancing operations or in developing incremental improvements, industry is unlikely to invest significantly in research programs that focus on longer-term or higher-risk high-reward initiatives. Additionally, because research necessary for nuclear power plant long-term operation is of a broad nature that provides benefits to the entire industry as well as the entire nation, it is unlikely that a single company will make the necessary investment on its own. Government cost sharing and involvement are required to promote the necessary programs that are of crucial, long-term strategic importance. A government/industry collaborative cost-sharing arrangement for RD&D is warranted to address the long-range, policy-driven goals of government and the acceptability and usefulness of derived solutions to industry.

Nuclear RD&D must consider and address economic competitiveness – essential to currently operating plants, the enabling of new plant construction, and U.S. competiveness in global markets.

Although the time horizon for this plan spans a decade (2018-2028), some members of the WG emphasized the need to focus on RD&D with more near-term benefit, especially in cases where RD&D solutions are already available, but face barriers and/or obstacles to implementation. Industry and DOE will review the list from this report and agree on accountabilities and areas for collaboration. For both industry and DOE RD&D, stability of nuclear RD&D funding is important.

1.2 Process for Report Development and Report Content

The purpose of this report is to recommend LWR RD&D activities at DOE-NE over the next ten years (the period 2018 -2028). This report not only encompasses current program areas but also explores activities that are beyond the current programs for the longer term.

This report is largely technology-specific rather than program specific. It was a joint effort among DOE, the national laboratories and the nuclear industry, in order to facilitate strong stakeholder engagement. It will provide guidance to DOE-NE managers for future budgets.

The Office of Light Water Reactor Technology (NE-72) is responsible for the development and implementation of this report. NE-72 engaged a Working Group of Subject Matter Experts (SMEs) from industry, national laboratories, academia and regulators to develop RD&D recommendations for this report. The members of the Working Group are listed in Appendix A. Appendix B provides the Working Group Charter. Appendix C lists 35 nuclear experts who provided input to the Working Group; input included briefings on current DOE-NE programs that support LWRs.

The Working Group established a detailed list of RD&D needs or recommendations for consideration by DOE. This information was developed without regard to whether the RD&D was already underway or for which organization(s) (i.e., DOE, EPRI nuclear industry, etc.) are or would be responsible for execution. In the discussions, the Working Group recognized that a good deal of the RD&D on these issues was already underway. However, the Working Group felt it was important to develop a comprehensive list for consideration. DOE will work collaboratively with EPRI and industry to determine whether existing RD&D should be expanded as well as which organization(s) should address the RD&D needs not currently underway. The complete list of prioritized RD&D topics with specific details is provided in Appendix D.

The Working Group undertook a systematic ranking process to prioritize its RD&D recommendations. Section 2 provides the results of that effort. Appendix E provides additional details on the Working Group's prioritization process.

The Nuclear Energy Advisory Committee (NEAC) Subcommittee on Reactor Technology will review and endorse, as appropriate, the report of the Working Group and recommend approval disposition to the full NEAC and subsequently to DOE-NE. DOE-NE management will provide subsequent direction for implementation of the LWR RD&D recommendations, likely informed by meetings with EPRI, industry, NEI and other stakeholders to identify new collaborative activities. DOE-NE would then evaluate the need to modify or expand existing programs and/or establish new programs to capture new work scope, and revise program plans and budgets, as appropriate.

2. RECOMMENDATIONS

The LWR RD&D Working Group developed a detailed list of RD&D suggestions and recommendations, which are provided in Appendix D. The Working Group then undertook a systematic ranking process, described in Appendix E. The results of the ranking process are not meant to be a strict set of priorities, but rather should provide insight into how the items generally ranked within the Working Group. Future discussions and investigation into these items could provide information that would support a change in these priorities or in their emphasis.

The results of this prioritization are provided below. Note that in general, many RD&D ideas are applicable to both new Advanced Light Water Reactor (ALWR) plants and currently operating plants.

2.1 Prioritized RD&D Recommendations

1. Materials R&D: reactor pressure vessel (RPV) and RPV internals, reactor coolant system integrity, concrete degradation, underground piping, cables, nondestructive examination.
2. Digital technology R&D: obsolescence issues, safety applications, control room design, human reliability analysis, NRC acceptance, pilot demos, etc.
3. Expanded cost-shared SMR licensing support beyond Design Certification (DC) to include Early Site Permit (ESP), Combined Operating License (COL), first-of-a-kind engineering (FOAKE); expand to include completion of a second SMR design.
4. Demonstration Projects (including cost benefit analysis for broad implementation of digital technologies) that provide enhanced monitoring diagnostics and predictive capabilities.

5. Expanded use of PRA and risk-informed and performance-based applications for plant operations management.
6. Advanced nuclear fuels with improved accident tolerance and improved efficiency and performance.
7. Enterprise risk models and communication tools to evaluate impacts of renewables, nuclear deployment strategies, premature nuclear retirements, grid reliability, and impact of various policies, such as the Clean Power Plan.
8. Ease of access and utilization of national lab and university assets for industry use at an acceptable cost and schedule.
9. Balance of Plant (BOP) materials issues: steam turbines, cooling towers, non-safety underground piping, turbine auxiliaries, etc.
10. Modeling and simulation: multi-physics, integration of plant models, improved computational tools to reduce uncertainty in safety margins, for current and future plants.
11. R&D on aging and obsolescence of mechanical and electrical equipment.
12. Realistic source term including radionuclide content, timing, dispersion, and associated regulatory impacts (e.g., emergency planning).
13. Advanced nuclear plant construction techniques: advanced manufacturing, modularization, factory fabrication, composite wall construction, supply chain enhancements, etc.
14. Cybersecurity solutions.
15. Robotics and automation of plant processes; O&M efficiency solutions.
16. Plant cooling water: alternate sources; alternate cooling technologies; water quality, reduced consumption.
17. Asset management: integrated risk and cost decision-making for in-plant use.
18. Expedited resolution of used nuclear fuel (UNF) management issues; implementation of Blue Ribbon Commission (BRC) recommendations.
19. Improved resilience to beyond design basis events.
20. Examination of follow-on LWR concepts (e.g., larger integral LWR reactors, higher efficiency GEN III+ designs, etc.).
21. Other new plant innovations: codes and standards, siting options (federal sites), floating plants, commercial grade dedication.
22. Realistic dose consequence models; eliminate inappropriate use of linear no-threshold (LNT) theory; benefits to emergency planning and siting.
23. New missions for nuclear: hybrid systems, process heat, desalination, etc.
24. Flexible power operations; load following capabilities and understanding of associated system impacts.
25. Improved training and qualification of nuclear plant staff.

26. Establishment of program for and qualification of advanced batteries for 1E nuclear applications (e.g., Valve-Regulated Lead Acid).

27. Low Level Waste (LLW) minimization.

28. Lithium-7 supply.

3. CHALLENGES

The Working Group received significant input on the current challenges facing nuclear energy in the U.S. In particular, ten senior utility executives and eight senior executives from reactor vendors and architect-engineering firms addressed the Working Group, many of them providing perspectives on challenges, in addition to their primary role of providing RD&D suggestions.

In the last three years, nuclear utilities have shut down, or announced their intent to shut down, eight nuclear reactors. These reactors were safe and well-performing plants, but many were severely impacted by adverse market conditions. Two new large LWR construction projects are underway (with two units at each plant) and one SMR design licensing effort is nearing submittal for NRC review. However, earlier predictions of multiple new plant orders have not materialized.

Efforts to address climate change mitigation without creating negative economic impacts on energy sector workers, electricity ratepayers, and taxpayers is bringing renewed focus on nuclear energy as an essential partner with renewables in national and worldwide energy policy. Notably, the potential for nuclear to replace retiring fossil fuel plants represents a key window of opportunity for the industry.

The challenges facing nuclear energy include:

- Historically low natural gas prices, resulting in markets where existing or new nuclear cannot compete profitably;
- Adverse market conditions that undervalue the unique attributes of nuclear energy, such as:
  - Federal and state mandates for renewable generation, which obscure the real operating costs;
  - Transmission constraints, which require power plants to pay a congestion charge to move their power onto the grid; and
  - Market designs that do not compensate dispatchable baseload nuclear plants for the value they provide to the grid.
- Rising nuclear O&M costs;
- Aging equipment – obsolescence;
- Increasing need for flexible power operations;
- Cooling water availability challenges;
- Regulatory demands and cumulative impacts of new regulatory requirements;
- Lack of public understanding and acceptance of nuclear power;
- Used nuclear fuel disposition, primarily in its impact on public understanding and acceptance of nuclear energy's important role in national energy policy; and

- Workforce issues: staffing for the future; training, attrition/retention, "new to nuclear" workers.

In addition to the items noted above, some utility executives were concerned about the growing complexity of the license renewal process, including uncertainty about what new regulatory requirements might emerge for second license renewal via the upcoming revision to the Generic Aging Lessons Learned Report, as well as the adverse trend in the timing and cost of the license renewal application and review process. Similarly, they expressed concern about regulatory uncertainty associated with SMR and Gen III+ plant licensing.

RD&D can contribute to the reduction/elimination of many of the challenges listed above. Many of the challenges identified by the senior nuclear executives are policy-related, but RD&D can inform and help change/shape policy.

Appendix A

Working Group Members

Appendix A
Working Group Members

Working Group Co-chairs:

- Kathryn A. McCarthy (INL, Director of Light Water Reactor Sustainability Program Technical Integration Office)
- Bradley J. Adams (VP Engineering, Southern Nuclear Operating Company)

Working Group Members:

- Chris Mudrick (Sr. VP, Mid Atlantic Operations, Exelon)
- Ed Halpin (Sr. VP and CNO, Pacific Gas & Electric Co.; Diablo Canyon)
- Regis Matzie (NEAC Member and Reactor Technology Subcommittee Member; retired Westinghouse Senior VP and CTO)
- John Wagner (ORNL, Director Reactor & Nuclear Systems Division)
- Hussein Khalil (ANL, Director Nuclear Energy and Security Program)
- John Ireland (retired LANL Program Director)
- Michael Corradini (University of Wisconsin, Professor of Nuclear Engineering; Member, NRC Advisory Committee on Reactor Safeguards)
- Kord Smith (MIT, Professor of Nuclear Engineering, co-founder and former Vice-President Technical Development, Studsvik Scandpower)
- Audeen Fentiman (Purdue University, Associate Dean of Engineering for Graduate Education and Interdisciplinary Programs / Professor of Nuclear Engineering)
- Dale Klein (former NRC Chairman; Associate Vice Chancellor for Research in the Office of Academic Affairs, University of Texas, Austin)
- Jason Remer (Director, Plant Life Extension, Nuclear Energy Institute)
- Tina Taylor (Director, Strategic Programs, Electric Power Research Institute)

Appendix B

Guidelines for Working Group

Appendix B
Guidelines for Working Group

NE-72 will engage a Working Group of subject matter experts (SME) as a working group under the NEAC Reactor Technology Sub-Committee. The working group will review appropriate material; discuss issues; engage stakeholders to receive briefings and provide recommendations for future LWR RD&D for a NEAC recommendation for DOE-NE consideration. This SME working group will consist of nuclear industry, laboratory, and university personnel with expertise in light water reactor technology. The working group will include NEAC Reactor Technology subcommittee members as well as a broad spectrum of stakeholder expertise from the nuclear industry, academic and research community. Two members of the LWR RD&D SME working group will be selected to co-chair/lead the effort and report the results to the NEAC Reactor Technology Sub-Committee and DOE-NE. It is envisioned that one chair will be from industry and one from a national laboratory. The NE-72 Deputy Director will participate/observe in the SME Working Group activities as the liaison with DOE-NE, not as an SME working group member.

The SME Working Group co-chairs will establish a list of RD&D topics for consideration and a schedule of activities, briefings and meetings to discuss and understand potential LWR research areas from their own experience and that of others in the nuclear industry and research community. The list of activities, briefings and meetings will be coordinated with the NE-72 Deputy Director for scheduling and logistic purposes.

It is expected that stakeholder organizations, such as the following, will be asked to brief the SME Working Group:

Reactor vendors

Commercial nuclear industry;

Electric power Research Institute (EPRI);

Nuclear Energy Institute (NEI);

Institute for Nuclear Power Operations (INPO);

Nuclear Regulatory Commission Office of Research (NRC-RES);

National Laboratories;

Universities

In addition, pending the topics identified for further discussion of RD&D, other stakeholder organizations may be identified to brief the SME Working Group. Other techniques such as Requests for Information (RFI) or open workshops may be used to gather information.

Following information gathering, the SME Working Group will develop a report identifying LWR research and development topics for future funded implementation. The SME Working Group Co-Chairs will present the results of this study to the full Nuclear Energy Advisory Committee (NEAC) or the NEAC Reactor Technology Subcommittee as directed by NE management.

Appendix C

Nuclear Experts who provided Input to the Working Group

Appendix C
Nuclear Experts who provided Input to the Working Group

Phoenix AZ, October 29-30, 2015

Kathryn McCarthy, Director of LWR Sustainability Program Technical Integration Office, INL

Tom Miller, Deputy Director, Office of LWR Technology, DOE-NE

Ed Halpin, Sr. VP and Chief Nuclear Officer, Pacific Gas & Electric Co.; Diablo Canyon

Brad Adams, VP Engineering, Southern Nuclear Operating Company

Jess Gehin, Director, Consortium for the Advanced Simulation of LWRs, ORNL

Rita Baranwal, Director Technology Development & Application, Westinghouse

Fran Bolger, Manager, New Product Introduction, GE-Hitachi

Marty Parace, VP, Products & Technology N.A. and Chief Technology Officer, Areva (Marty could not attend; Paul Murray, Areva, gave Marty's presentation)

Keyes Niemer, Vice President Operations, BWXT

Jose Reyes, Chief Technology Officer, NuScale/Fluor

Jack Cadogan, Vice President, Nuclear Engineering, Arizona Public Service

Tina Taylor, Director, External Affairs, Nuclear, EPRI

Myron Kaczmarsky, Senior Director, Business Development, Chicago Bridge & Iron

Desmond Chan, Chief Technology Officer, Bechtel

Go-To webcast, November 24, 2015

Richard Griffith, Sandia National Laboratory

Per Peterson, UC Berkeley

Lee Pedicord, Texas A&M University

Chris Mudrick, Sr. VP, Mid Atlantic Operations, Exelon

Tom Marcille, VP of Reactor Technologies, Holtec

Washington DC, December 10-11, 2015

Marilyn Kray, Vice President Nuclear Technology and Strategy, Exelon Generation Co.

Brianne Miller, Staff Member, Committee on Energy and Natural Resources, U.S. Senate

Vince Gilbert, Senior Fellow, U.S. Nuclear Infrastructure Council

Robert Braun, President and Chief Nuclear Officer, PSEG

Bill Pitesa, Senior Vice President and Chief Nuclear Officer, Duke Energy

Bryan Hanson Sr. VP, Exelon Generation; President and Chief Nuclear Officer, Exelon Nuclear

Kemal Pasamehmetoglu, Associate Laboratory Director, Nuclear Science and Technology, INL

Bill Webster, Executive Vice President, Industry Strategy, INPO

Tony Pietrangelo, Senior Vice President and Chief Nuclear Officer, NEI

Jennifer Uhle, Deputy for Reactor Safety Programs, Office of Nuclear Reactor Regulation, NRC

Mike Case, Director. Division of Engineering, Office of Nuclear Regulatory Research, NRC

Gene Grecheck, American Nuclear Society President, retired Vice President, Nuclear Support Services, Dominion Nuclear

Go-To Webcast February 4, 2015

Lisa Edgar, Florida Public Service Commissioner; Past President. National Association of Regulatory Utility Commissioners

David Lockbaum, Director, Nuclear Safety Project, Union of Concerned Scientists)

Dave Heacock, President and Chief Nuclear Officer, Dominion Generation (Delayed to 15 Feb.)

Atlanta GA, February 25, 2016

This meeting devoted to ranking of inputs

Appendix D

Detailed List of Working Group Inputs

Appendix D
Detailed List of Working Group Inputs

The following listing of recommendations includes key details or examples of specific RD&D needs within each recommendation. Note that this list was developed without eliminating RD&D items that are already underway in DOE, EPRI, and/or industry programs. The details under each recommendation come from the stakeholders that provided input to the Working Group. The details are included as examples of things that could be considered as this list is further examined, however the working group made no attempt to refine or prioritize the detailed items.

1. **Materials R&D: reactor pressure vessel (RPV) & RPV internals, reactor coolant system integrity, concrete degradation, underground piping, cables, nondestructive examination.**

<u>RPV Integrity</u>

- RPV degradation
- R&D to support RPV thermal annealing (or RPV replacement in limited cases)

<u>Other RCS material issues</u>

- Long term thermal embrittlement of RPV internals
- Nozzle weld cracking
- Impact of aging on individual plant components such as valves and sprinkler spray heads
- Environmentally assisted fatigue; corrosion fatigue, stress corrosion cracking, crack growth in welds
- Impact of aging on seismic load effects
- Advanced welding technologies for repair of embrittled components

<u>Improved steam generators</u>

<u>Advanced volumetric inspection techniques</u>

<u>Other Safety-Related Mechanical Systems</u>

<u>Used Fuel Pools</u>

- Improved neutron absorbing materials

<u>Underground Piping</u>

- Response to high pressure corrosion
- Innovative structural inspection, repair and preservation methods for buried pipe

<u>Electrical Cables</u>

- Cable inspection program
- Insulation degradation and high temperature locations

<u>Advanced NDE Technologies</u>

- Concrete NDE
- Cable NDE
- RPV NDE

Advanced Materials Development

- New ceramics and polymers for BOP application
- Advanced micro/nano chemistry characterization (microchemistry techniques)
- Advanced micro-mechanical measurements (direct measurement and calculation)
- Carbon / carbon composites

Containment Concrete Support Structures Subject to Long Term Radiation / Aging Degradation.

- Improved technologies for inspection and monitoring of concrete structure structural integrity
- Long term concrete aging effects, including radiation degradation

2. Digital technology R&D: obsolescence issues, safety applications, control room design, human reliability analysis, NRC acceptance, pilot demos, etc.

Safety Applications; Overcoming Difficulty of Adoption of Digital Technology

- Technical basis for a risk-informed (RI) approach to I&C surveillances
- Reliability and dependability of software
- Address common cause failure; establish regulatory criteria for how much diversity is needed for digital systems
- Support for plants transitioning to digital control systems, to include pilot demonstrations
- Strategy for wholesale replacement of analog I&C (both safety and control) rather than a gradual system by system approach where some is digital and some is analog over a sequence of operating cycles.)

Human Reliability Analysis (HRA) and Human Factors Engineering (HFE)

- Technical bases for rapidly evolving concepts of operation and control room technologies for new plants to satisfy NRC requirement for “state-of-the-art” human factors
- HRA methods that are designed for automation (including adaptive and/or digital I&C systems)
- Identify means for providing regulatory credit for industry initiatives that improve human performance (e.g., FLEX, ROP, RI licensing actions)
- HFE for multi-unit control rooms (typically for SMRs)
- HFE for operations and maintenance functions, electronic work packages, etc.

Advanced Sensors; Advanced Monitoring Techniques, Including Greater Remote Capabilities

- Increased remote monitoring and trending
- Wireless sensors to reduce costs compared to hard-wired sensors

- On-line and central remote monitoring to eliminate system and component performance monitoring burden from the plant site.
- Sensors and instrumentation in high hazard environments (including equipment qualification), under water, high fluence, high temperature)
- Acoustic methods for measuring in-core power

Digital Power Plant: Predictive Analytics; Integrating Advanced Sensors into Complete System

- Incorporate 3-D plant models into maintenance and repair planning
- Inform O&M decisions based on sensor / maintenance / log data
- Integrate sensor information with model of plant (including core, T/H systems, and controls); optimize plant thermal performance
- Evaluate and/or predict plant safety performance

Fleet-wide Monitoring and Management

- Develop technologies supporting new plant fleet management, similar to how this is done in the aircraft industry

.

3. Expanded cost-shared SMR licensing support beyond Design Certification (DC) to include Early Site Permit (ESP), Combined Operating License (COL, first-of-a-kind engineering (FOAKE); expand to include completion of a second SMR design.

- Build a national strategic plan for SMRs that ensures SMRs are supported through the entire journey from concept to implementation.
  - Initiate a Nuclear Power 2010 type SMR program to help fund the full implementation of SMRs. This should include co-funding for COLs and FOAKE, and getting a second design moving forward to add competition
- Support siting of future nuclear plants, including cost-shared support for companies seeking ESPs for suitable sites, including retiring coal-fired plants.
- Examine innovative licensing strategies to dramatically reduce time and cost of licensing.
- Develop data and analysis capability to perform and/or contribute to economic analyses of the costs of construction and operation of current and future plants to focus RD&D
- Identify ways to reduce the need for safety class systems, structures and components
- Continue support to industry efforts to resolve generic licensing issues for SMRs, such as source term simplification and associated testing.

4. Demonstration projects (including cost benefit analysis for broad implementation of digital technologies) that provide enhanced monitoring diagnostics and predictive capabilities.

- These are specifically demonstration projects that support implementation of large sets of digital technologies as opposed to demonstration of implementation of individual digital technologies.

- A business case analysis should be done to support these demonstration projects.

5. Expanded use of PRA and risk-informed and performance-based applications for plant operations management.

- Expand use of PRA as a prioritization tool. Over-commitment beyond regulations creates a major economic burden.
- Develop integrated and dynamic PRA methods to address the temporal importance of passive and active system response, actions and evolution of the outcomes.
- Improved means to address uncertainty (e.g., refinement of analytical methodologies for the characterization and propagation of uncertainty)
- Exploit results of ongoing NRC-Southern Co. Vogtle Level 3 PRA: safety improvements and burden reduction (e.g., RI-in-service inspection, RI-tech specs, etc.).
- Improve realism and modeling in Fire PRAs; quantify RI-performance based scenarios
- Risk informed safety margins characterization of LWRs for external (seismic) hazards
- Risk informed approach to security (review DOE's 2003 Security Roadmap for ideas); match numbers of security staff with realistic threats in U.S., not hypothesized threats; automation to reduce workforce.
- Managing physical security with a simulation capability to reduce regulatory oversight.
- Risk informed and performance based design for seismic safety

6. Advanced nuclear fuels with improved accident tolerance and improved efficiency and performance.

>5% enrichment and higher burn-up fuel

- Evaluate higher enrichment fuel (~6%) to get up to a 2-year operating cycle with improved clad materials. What is the optimum % increase? (EPRI /DOE studies 10-15 years ago suggested optimum is in 6-8% range.)
- Evaluate options to achieve benefits such as getting to 24 month fuel cycles, especially for PWRs, without increased enrichment limits: conduct analyses that provide the basis to eliminate the current burnup limit of 62 GWD/MTU; explore higher density fuels and optimum burnup.
- Evaluate potential of additive manufacturing for varying pellet fuel enrichment and integral absorber content to achieve 24 month fuel cycles without increased enrichment.

Accident tolerant fuel: improve alignment of vendors, utilities, national labs, EPRI, and other industry organizations to produce a more focused approach to designing ATF

- Look at ATF in an integrated manner: reactor design implications, future operation of reactors, performance under design basis accidents and beyond design basis accidents, relationship to load following, etc.

Identify most cost-effective fuels options for new LWRs

Fuel in natural circulation plants (mostly related to some SMRs)

- Develop innovative fuel pin/assembly designs to enhance natural circulation flow
- Research new fuel forms, fuel pin configurations, and fuel assembly designs that offer reduced pressure drop across the core. Research would focus on optimizing core design for pressure drop while maintaining traditional core metrics.

7. Enterprise risk models and communication tools to evaluate impacts of renewables, nuclear deployment strategies, premature nuclear retirements, grid reliability, and impact of various policies, such as the Clean Power Plan.

Develop integrated financial models of the installed base that account for merchant and regulated unit economic drivers are necessary to demonstrate continued viability of current and new plants, especially when evaluating modifications or new revenue streams. Such a model should include:

- Model various electricity market reforms, including FERC guidelines, state and regional reforms, including reforms to both regulated and unregulated markets.
- Capability to examine nuclear business case; more than just CAPEX and OPEX decisions and weighted cost of capital
- Address complex capacity auctions impact on economic viability
- Variable generation costs and electricity pricing by hour/day/month.
- Evaluate carbon tax or carbon cost savings.
- Capability to conduct long term cost benefit analysis

Examine energy policy options to demonstrate continued viability and value of nuclear

- Conduct tradeoff studies to inform policy challenges. These studies must be tailored to the intended audience. Need to show numbers to influence policy.
- Effects of renewables and renewable pricing on grid stability and grid contracts including state-by-state requirements.
- Evaluate increased use of pumped storage
- Evaluate premature plant closure scenarios to show local / regional economic impacts; analyses should address effects of plant closures on grid reliability
- Effects of Clean Power Plan, potential federal and state-level laws and initiatives, and other policy variables related to climate change response
- Evaluate impacts such as additional carbon resulting from replacement generation, economic and grid stability.
- Evaluate reliability benefit of nuclear in inclement weather, e.g., frozen coal piles, and constrained pipeline capacity during high demand periods.
- Evaluate NPP new construction scenarios, assumptions and designs, including economic benefits to specific regions and markets
- Evaluate international markets and U.S. policy options that allow U.S. to compete

- Trade-off studies to examine ultra-power uprates and conversion system innovation (as might accompany higher burnup/higher enrichment fuels)
- Options to introduce advanced fuel concepts, including HBU fuel and ATF, along with associated impacts on plant refueling cycles, resultant front-end fuel economics, potential to simplify emergency planning, etc.

Communications tools that clearly explain the importance of LWR technology in addressing issues of concern (e.g., on-site storage of UNF, safety, siting). Messages must be understandable and credible, and must convey nuclear's economic, safety, environmental, and reliability value in context: valuable long term investment.

- Consider role for DOE senior management in communicating analysis results

8. Ease of access and utilization of national lab and university assets for industry use at an acceptable cost and schedule.

Make national lab assets more accessible to industry for development and testing of concepts; provide industry with single point easy access to broad range of capabilities

R&D Test Bed Assets:

- Test reactors
- Hot cells
- State-of-the-art experimental capabilities
- Fuel fabrication, qualification, and testing
- Destructive and non-destructive fuels and materials examination
- Computational power and modeling and simulation capabilities
- Digital I&C test bed
- Other basic R&D needs

Provide site for Demonstration Reactor Deployment to address economic/operational feasibility

- INL and other Federal sites (extensive infrastructure support)
- Public (federal)-private partnerships
- Regulatory interface
- Financing options

9. Balance of Plant (BOP) materials issues: steam turbines, cooling towers, non-safety underground piping, turbine auxiliaries, etc.

Non-Safety Class Outdoor Structures (e.g., Cooling Towers)

- Structural concrete subject to long term degradation, with wetted structures at higher risk
- Innovative structural repair and preservation methods for non-safety concrete structures

Steam Turbines

- Probability analysis for turbine missiles (provide basis for eliminating or decreasing required frequency for disassembly for inspection and NDE)

Reduced crud deposits to steam generators

- Ultrafine filtration (nano-filtration) – reduced crud and reduced deposits to steam generators

Non-safety Underground piping (e.g., fire water)

10. Modeling and simulation: multi-physics, integration of plant models, improved computational tools to reduce uncertainty in safety margins, for current and future plants.

- More accurate neutron and gamma fluence predictions on RPV and internals away from core
- Improved speed and accuracy of complex structural models.
- 3-D modeling of material micro-structures to improve predictions of age-related degradation
- Full plant model – integration of all plant models
- Greater use of simulation tools for design, construction, and maintenance activities to reduce construction and operating risk.
- Improved computational tools to reduce uncertainty in safety margin
- Sustainable business plan for industry adoption, use and maintenance of integrated tools (e.g., MOOSE, RISMC, and CASL), including regulatory acceptance
- Full spectrum LOCA analysis (basis to simplify or eliminate existing LBLOCA basis)
- Modeling of containment pressure release approaches (e.g., charcoal filters)
- Develop multi-physics methods that can used to produce “simulated” test data.
- Technical and data analyses and risk-based computer modeling to resolve ongoing regulatory issues, such as external events (wind, seismic, flooding, fire), plant security, emergency preparedness, etc.; and/or technical support to streamline, simplify, and reduce the cost of implementing new regulations and regulatory requirements. Focus on reducing time/cost of licensing analyses and reducing unnecessary conservatism.
- Expand/grow R&D in data science

Modeling and Simulation needs of SMRs

- Transient and accident analyses for integral PWR systems including natural circulation systems
- Dynamic PRA for nuclear plants; also as a cross-cutting method for risk-inherent engineered systems such as petro-chemical plants (of interest when coupling an SMR to an industrial process heat user)
- Address external hazards for SMRs e.g., risk factors unique to new designs

11. R&D on aging and obsolescence of mechanical and electrical equipment.

- Mechanical and electrical equipment critical to long term plant operation
- Advances in predicting lifetimes of critical SSCs from materials perspective
- Maintenance/modification and bridging/ replacement strategies
- Improve in-service inspection, diagnostic, maintenance and repair techniques
- Mechanistic and predictive models for evaluation of safety implications of flawed and/or aged components

12. Realistic source term including radionuclide content, timing, dispersion, and associated regulatory impacts (e.g., emergency planning).

- Realistic source term, including radionuclide content, timing, dispersion, and associated regulatory impacts (e.g., emergency planning)
- Update outdated codes and methods for radiation protection that over-estimate dose risks; apply improved realism to offsite consequence analyses, siting, emergency response, etc.

13. Advanced nuclear plant construction techniques: advanced manufacturing, modularization, factory fabrication, composite wall construction, supply chain enhancements, etc.

<u>Advanced Manufacturing for new plants</u>

- Hot Isostatic Processing (HIP) for manufacturing LWR, SMR, and ALWR components
- Qualify advanced factory-based manufacturing technologies:
- Advanced welding techniques
- Laser cladding
- Hybrid Laser Welding
- Factory inspections, tests, analyses, and acceptance criteria (ITAAC)
- CT Image for as-built dimensions; inspections; and automated development of input decks for safety analysis codes
- Technology enhancements to improve quality (e.g., managing tolerances)

<u>Additive Manufacturing Processes:</u>

- Friction stir additive manufacturing
- Direct metal laser sintering (DMLS)
- Microstructure (and cost) management through machine control and modeling
- Additive polymers that meet IEEE requirements (relays)

<u>Supply Chain and Facility Enhancements for New Plants</u>

- Identify and recommend U.S. facilities that can perform advanced manufacturing for new plants; if new facilities are required identify what areas of manufacturing are needed.
- Replicate supply chain processes such as are used for commercial/military aircraft.
- Develop dynamic modeling and simulation for nuclear supply chain optimization for SMRs; identify future supply chain technical issues
- Extend model to evaluate M&O cost, evaluate levelized cost of electricity (LCOE); integrate design and supply chain
- Modeling and simulation of the potential gains and issues of the nuclear supply chain to support new plant manufacture and deployment.

<u>New Construction Techniques Associated With Containment Systems and Structural Concrete.</u>

- Composite wall concrete/steel inspection capability; performance monitoring/condition assessment of composite modular structures, such as AP 1000 shield building
- Advanced reinforced concrete materials for new construction, rehabilitation and repair:
- Seismic Isolation: (largely SMR-specific)
- DOE cost-shared support for design of an advanced manufacturing facility (factory).
- Extend existing DOE generic support programs such as loan guarantees and investment tax credits to deployment of SMR factories.

14. Cybersecurity solutions.

- Security control testing (penetration testing) and vulnerability validation in operating environments; consider using shutdown plants for cybersecurity testing
- Advanced security monitoring and log analysis, including correlation of operating parameters (event analysis and response)
- Cyber impact analysis methodology for digital upgrades
- Narrow the focus of cybersecurity programs based on consequences (screen out possible vulnerabilities with no significant consequences)

15. Robotics and automation of plant processes; O&M efficiency solutions.

<u>Robotics, especially for outage work in high rad areas</u>

- Mobility challenges (ladders, tight spaces, etc.)
- Vision systems that can facilitate real time data for decision making
- Continue with advanced capabilities of nuclearized robotics for integrated mapping (IRP-EM-1) for LWR applications. Example: GE Railcar Robotics Inspection Strategy
- Expand robotics use in tanks, pools, pipelines, etc.
- Expand robotics use in NDE/NDT
- Underwater robotics, including options for tether-less robotics

  - Accurate global positioning (mm accuracy) is a challenge for inspection and repair tooling
  - Small / fast scanning tools for tight spaces
- All robotics systems should consider radiation tolerance

Automation of O&M processes

- Automated chemistry analysis
- Automated radiological analysis
- Remote monitoring – tele-dosimetry, OSHA, GPS personnel tracking
- Automatic generation of ALARA job reviews and RWPs
- Inspections
- Adaptive automation
- Greater standardization of processes across plants to reduce costs

R&D solutions to support industry cost initiative, e.g., means to reduce/simplify/eliminate excessive Corrective Action Reports.

16. Plant cooling water: alternate sources; alternate cooling technologies; water quality, reduced consumption.

Alternate Water Sources

- Ground water sources (poor quality)
- Evaluating underground storage (water table charging and recovery)
- Reclaimed water

Alternate Cooling Technology

- Focus on alternate cooling technology to reduce water usage, including lower consumption cooling towers.
- Consider National Science Foundation/EPRI dry cooling technology innovation program
  - Most viable near term option is "thermosiphon" using dry / air-cooled condensers. (EPRI supplemental program proposed for this)
- Water saving technologies (practical applications for water use reduction and filtration)

Water Quality and Consumption

- Water quality impacts (usage, discharge and impact on systems)
- Reduce water consumption through increased water quality and resulting increased number of cycles of concentration
- Technology for large scale filtration needed
  - Compensate for expected increase in effluent total dissolved solids (TDS)
  - Reduced impact on concrete structures and cooling water systems

- Reduced potential for additional evaporation pond area

Cooling Water for SMRs and ALWRs

- Investigate strategies to enable new nuclear plants to utilize existing cooling water intake structures at retiring fossil plants (avoiding construction of cooling towers). Investigate options to enable continued use of once-through cooling, such as deep water intakes, improved fish protection technologies, etc.

17. Asset management: integrated risk and cost decision-making for in-plant use.

- In order to examine a wide range of technology and operational opportunities, industry needs better analysis tools that couple the risk insights from PRA to cost-benefit insights, to allow decision makers a straightforward means to make risk-cost trade-off decisions.
- Need an Asset Management tool to evaluate the cost side of decision-making – we need to look at cost-benefit trade-offs, not just relative safety benefits.
- Tool to measure current / future RD&D programs impact on both O&M cost and safety.
- Tools for cost effective strategic planning
  - Optimize repair vs. replacement decisions
  - System health and condition-based maintenance monitoring
  - Long range plans (large capital replacements and modifications)
    - System health and condition-based maintenance monitoring
    - Living cost basis preventative maintenance (non-safety class)
- Tools to prioritize plant workload (greatest benefits at least cost and manpower impact); tools to help address "cumulative impacts of regulation."
  - Cost-benefit analysis methodologies
- Very long term strategic planning – Operation beyond 80 or 100 years
  - Enterprise costs and risks; support evaluating long-term operation of plants
  - Design Guide to 80/100; address constructability/maintainability/operability
- Integrated/common safety/economic analysis tools
- Tools to apply asset management concepts and insights to new plants, e.g., optimum design margins, ease of major component replacement, pre-installed SSC monitoring
- "Big Data" – mining operating experience to maximum benefit (condition-based monitoring, anticipating problems, etc.)

18. Expedited resolution of UNF management issues; implementation of Blue Ribbon Commission (BRC) recommendations.

- RD&D for long term dry used fuel storage, focused on consolidated storage at a central facility away from existing reactor sites. Implement recommendations by the President's Blue Ribbon Commission on America's Nuclear Future (2012)
- Uranium mining techniques (more efficient and environmentally friendly)

- Examine uranium fuel supply projections to verify stable long term fuel prices

19. Improved resilience to beyond design basis events

- Options for ex-vessel coolability / in-vessel retention
- Bolt-on Passive Systems for long term or indefinite cool-down systems, such as “New Vision” system – passive system that introduces cooling during SBO – using steam off the steam line. Eductor concept. Some proprietary considerations. How to license? If licensable, how could industry get regulatory credit?
- Fukushima Lessons learned (largely identified and addressed by FLEX. However, LWRS is following up on potential areas of fruitful research, such as long term survivability of RCIC in BWRs, accident data for BWR severe accident codes, etc.)
- Use data from Fukushima to help reduce uncertainties in severe accident analysis
- Use decommissioning and forensic analysis to inform cleanup and waste management technologies (e.g., remote inspection methods, robotics, etc.)

20. Examination of follow-on LWR concepts (e.g., larger integral LWR reactors, higher efficiency GEN III+ designs, etc.).

- Licensing process improvements for next-generation reactors
- Examine lessons learned from new plant construction in the U.S., China, and the EU to identify greatest benefits at lowest cost.
- Examine feasibility of GW-size integral reactor (economies of scale applied to SMRs)
- Examine feasibility of major upgrades to GEN III+ designs to reduce cost and construction schedule, and/or increase power output
  - Once-through steam generators to increase efficiency
  - Materials/chemistry changes to enable TH >625oF

21. Other new plant innovations: codes and standards, siting options (fed. sites), floating plants, commercial grade dedication.

- Examine feasibility of demo plant and/or DOE licensing initial SMR if built on DOE site
- Codes and Standards updates to support new plants
- Chemistry guidelines for SMRs
- Chemistry guidelines for future fuel forms (e.g., ATF concepts, SiC cladding)
- Inspection Standards and Frequencies for SMRs
- Infrastructure for installing/acceptance of SMRs on a non-nuclear site (old fossil site)
- O&M that supports reduced staffing

- Support building SMRs on Federal facilities: DOD/Federal Facilities that need critical power.
- Shipyard construction of deep-water, floating plants (to reduce construction cost/time)
- Exploit Commercial Grade Dedication experience from current plants to overcome licensing hurdles for new plants.
- Inspection ports for critical areas
- Multi-unit control rooms
- Greater standardization of SSCs to reduce costs

22. Realistic dose consequence models; eliminate inappropriate use of linear no-threshold (LNT) theory; benefits to emergency planning and siting.

- Realistic dose consequence models; eliminate inappropriate use of linear non-threshold (LNT) theory; benefits to emergency planning and siting

23. New missions for nuclear: hybrid systems, process heat, desalination, etc.

- Competitive solutions for nuclear's role in nontraditional applications:
  - Electricity
  - Process Heat
  - Desalination
  - Policy Driven Demand
  - Integrated systems with alternate products (poly-generation)
- Hybrid Energy Systems: To meet the nation's clean energy goals, it will be necessary to use nuclear energy to support process heat users, either in a dedicated fashion, in co-generation mode, or within a network of multiple energy producers and users (hybrid energy systems).
- Develop interface technologies to facilitate coupling of new plants to hybrid energy systems

24. Flexible power operations; load following capabilities and understanding of associated system impacts.

- Advanced reactor control methods to facilitate balancing of multiple loads and automated power maneuvering. Control system for economic dispatch; address fuel, control valves, pumps, etc. Validate against realistic scenarios, e.g., nuclear backs up renewables
- Power changes result in additional cycles on systems, structures or components, with impacts on equipment, fuel and operations; other long range planning/LTO impacts
  - Impacts require better fatigue modeling and transient modeling capability
  - Biggest cost impact of LF may be primary coolant water management
  - Reactor vessel internals, nozzles, steam generator tube wear, etc.
  - Fuel reliability and enrichment impacts (with LF, we are throwing fuel away).

- Maintenance of components.
- Cycling of structural components
- General “wear and tear” impacts

- Cost study on implementing LF
- Examine implications of FPO to new plants early – at the design stage
- Examine feasibility of backfitting “gray rods” (as used in AP1000) to current plants
- Clearly define the load-following capabilities of existing reactors and ALWRs
- Define what is needed in the future grid for the highest projected percentage of renewable energy (in the context of what nuclear plants can do)

25. Training and qualification of nuclear plant staff.

Training and Qualification

- How can industry do training faster and cheaper? Need to fix the current paradigm that requires 2-3 years of training before a new employee is allowed to do anything at a plant. Hugely discouraging to new employees.
- Three-phased problem:
  - Retraining of (“ThisGen”) workforce
  - Training of young (“NextGen”) workforce
  - Retention of (“LastGen”) expertise
- Need to use more hands-on/virtual techniques
- Young people entering the industry have a different perspective:
  - Working conditions and career expectations
  - Comfort with modern digital world, software, devices, etc.
  - Using and interpreting data.
- Biggest hurdle to more efficient / innovative training is INPO requirements. INPO acknowledges that training needs to evolve, quickly, with greater reliance on modeling and simulation
- Problem is much larger than engineering training. Also need operators, rad techs, chemistry techs, etc.
- Training must utilize the latest in knowledge management, apprenticeship programs, college specialty programs

Exploit U.S. educated students from other countries to gain strategic advantages for U.S. nuclear industry, including U.S. leadership in safety and R&D:

- Sponsor internships in U.S. under the NEUP program.
- Collaborate with former graduates who are now leaders in overseas nuclear programs

26. Establishment of program for and qualification of advanced batteries for 1E nuclear applications (e.g., Valve-Regulated Lead Acid).

27. LLW minimization.

- Low level waste minimization, including insights from decontamination and decommissioning (D&D) experience.

28. Lithium-7 supply.

Appendix E

Prioritization Process

Appendix E
Prioritization Process

The prioritization process applied to the RD&D ideas in Appendix D by the Working Group was a structured four-step process, facilitated by a versatile software program, ThinkTank.

ThinkTank is a structured collaboration system hosted on an enterprise platform that can be accessed from a web browser on any electronic device, such as a tablet, laptop, personal computer, or smartphone. It enables leaders to engage groups of people in dynamic and anonymous (if preferred) conversations anytime, anywhere.

ThinkTank was used to enable efficient and effective collaboration of the Working Group from their remote locations to continue their progress towards reaching their goal in a timely manner.

The Working Group implemented the following four-step structured approach to the decision analysis and prioritization process:

- Establish criteria
- Rank criteria to achieve "weighted criteria"
- Summarize/consolidate detailed RD&D ideas into a short list for use in ranking
- Rank RD&D ideas using the weighted criteria.

Using ThinkTank to enable this structured approach, the Working Group members submitted their suggestions on appropriate criteria, assigned weights to the criteria, and utilized the average weights generated by the system as the weighted multipliers to rank the RD&D ideas. This information was captured in ThinkTank between February 8 and 22, prior to the face-to-face meeting on February 25, allowing time for individuals to think deeply about the criteria necessary to accomplish such a significant evaluation and provide their input when it was convenient for them. Final rankings were established during the February 25 meeting.

Also, with this information in ThinkTank prior to arrival, the Working Group was able to focus their attention on ensuring everyone clearly understood the RD&D ideas being proposed (generated from previous Working Group collaboration efforts), and on providing clarity, when needed. This ensured a more consistent understanding of the ideas being evaluated.

Through the use of ThinkTank, Working Group members were allowed time to think about the current and future of LWR technology strategy, engage freely, and contribute their best thoughts, at their most convenient time.

RESULTS

Step 1: The Working Group established the following criteria:

1. Has potential to streamline regulatory approval process.
2. Has potential to decrease plant O&M costs
3. Supports plant owner/operator decisions on whether to pursue license renewal and/or new build

4. Has potential to reduce capital investment(s) in operating plants.
5. Has the potential to expedite the development and implementation of new plant or fuel features
6. Supports the development of highly qualified plant staff
7. Supports the plant's efficient implementation of a regulatory requirement
8. Has the potential to significantly reduce the construction time and/or cost of new plants
9. Improves monitoring of plant operating conditions
10. Has the ability to reduce refuel outage durations and/or improve plant capacity factor
11. Increases plant safety margins
12. Key enabler for license renewal application.
13. Enhances capability for flexible power operation in response to electricity market conditions
14. Has potential to enhance support for nuclear power

Step 2: The criteria above were ranked by the Working Group. The following weighting factors resulted:

No.	Criteria	Weight
1	Has potential to streamline regulatory approval process.	5.64
2	Has potential to decrease plant O&M costs	9.00
3	Supports plant owner/operator decisions on whether to pursue license renewal and/or new build	6.09
4	Has potential to reduce capital investment(s) in operating plants.	8.00
5	Has the potential to expedite the development and implementation of new plant or fuel features	5.91
6	Supports the development of highly qualified plant staff	4.73
7	Supports the plant's efficient implementation of a regulatory requirement	5.55
8	Has the potential to significantly reduce the construction time and/or cost of new plants	7.55
9	Improves monitoring of plant operating conditions	5.27
10	Has the ability to reduce refuel outage durations and/or improve plant capacity factor	7.36
11	Increases plant safety margins	4.91
12	Key enabler for license renewal application.	7.00
13	Enhances capability for flexible power operation in response to electricity market conditions	6.27
14	Has potential to enhance support for nuclear power	5.82

Steps 3 and 4: An abbreviated listing of RD&D ideas was developed by INL and DOE staff for the Working Group, based on the Working Group's detailed list of RD&D ideas provided in Appendix D. This process consolidated specific ideas into sub-categories, being careful to retain specific items that were discrete (not amenable to consolidation into larger categories). This process resulted in a listing of about 35 RD&D ideas for use by the Working Group during the Feb 25 meeting. The group ranked these ideas against the weighted criteria. During this process, a few ideas were reworded and/or merged by the Working Group. The final list of summarized recommendations appears below.

Prioritized RD&D Recommendations

1. Materials R&D: reactor pressure vessel (RPV) and RPV internals, reactor coolant system integrity, concrete degradation, underground piping, cables, nondestructive examination.
2. Digital technology R&D: obsolescence issues, safety applications, control room design, human reliability analysis, NRC acceptance, pilot demos, etc.
3. Expand cost-shared SMR licensing support beyond Design Certification (DC) to include Early Site Permit (ESP), Combined Operating License (COL, first-of-a-kind engineering (FOAKE); expand to include completion of a second SMR design.
4. Demonstration Projects (including cost benefit analysis for broad implementation of digital technologies) that provide enhanced monitoring diagnostics and predictive capabilities.
5. Expanded use of PRA and risk-informed and performance-based applications for plant operations management.
6. Advanced nuclear fuels with improved accident tolerance and improved efficiency and performance.
7. Enterprise risk models and communication tools to evaluate impacts of renewables, nuclear deployment strategies, premature nuclear retirements, grid reliability, and impact of various policies, such as the Clean Power Plan.
8. Ease of access and utilization of national lab and university assets for industry use at an acceptable cost and schedule.
9. Balance of Plant (BOP) materials issues: steam turbines, cooling towers, non-safety underground piping, turbine auxiliaries, etc.
10. Modeling and simulation: multi-physics, integration of plant models, improved computational tools to reduce uncertainty in safety margins, for current and future plants.
11. R&D on aging and obsolescence of mechanical and electrical equipment.
12. Realistic source term including radionuclide content, timing, dispersion, and associated regulatory impacts (e.g., emergency planning).
13. Advanced nuclear power plant construction techniques: advanced manufacturing, modularization, factory fabrication, composite wall construction, supply chain enhancements, etc.
14. Cybersecurity solutions.
15. Robotics and automation of plant processes; other O&M efficiency solutions.

16. Plant cooling water: alternate sources; alternate cooling technologies; water quality, reduced consumption.
17. Asset management: integrated risk and cost decision-making for in-plant use.
18. Expedited resolution of UNF management issues; implementation of Blue Ribbon Commission (BRC) recommendations.
19. Improved resilience to beyond design basis events.
20. Examination of follow-on LWR concepts (e.g., larger integral LWR reactors, higher efficiency GEN III+ designs, etc.).
21. Other new plant innovations: codes and standards, siting options (fed. sites), floating plants, commercial grade dedication.
22. Realistic dose consequence models; eliminate inappropriate use of linear no-threshold (LNT) theory; benefits to emergency planning and siting.
23. New missions for nuclear: hybrid systems, process heat, desalination, etc.
24. Flexible power operations; Load following; system impacts.
25. Improved training and qualification of nuclear plant staff.
26. Establishment of program and qualification of advanced batteries for 1E nuclear applications (e.g., Valve-Regulated Lead Acid Batteries).
27. Low Level Waste (LLW) minimization.
28. Lithium-7 supply.