Appendix A

Working Group Report on – Space Nuclear Power Systems and Nuclear Waste Technology R&D

Nuclear Energy Research Advisory Committee

Subcommittee for Long Term Planning for Nuclear Energy Research

Summary Report
Nuclear Waste Technology and Space Nuclear Systems R&D Working Group
October 18-20, 1999 Workshop

NERAC Subcommittee on Long-Term Nuclear Research and Development Planning
Workshop I Report
Oct. 18-20, 1999

INTRODUCTION

"Even though one cannot anticipate the answers in basic research, the return on the public's investment can be maximized through long-range planning of the most promising avenues to explore and the resources needed to explore them." (p. v) "Pursuit of this goal entails developing new technologies and advanced facilities, educating young scientists, training a technical workforce, and contributing to the broader science and technology enterprise?." (p. vi)
Ref:: "Nuclear Science: A Long Range Plan", DOE/NSF, Feb. 1996.

The purpose of this effort is to develop the first iteration of a long-range plan for nuclear energy in the Department of Energy. It is desirable to update, expand, and improve this plan every few years. The focus must NOT be on next year's budget nor that for the next few years. Rather, the focus is on what is necessary to develop over the next 10-15 years. The approach to be taken is to begin with DOE as a whole, then narrow to NE.

Working Group 1 Summary Report
Nuclear Waste Technology and Space Nuclear Systems R&D

This group addressed long-term planning for disposition of radioactive materials, development of space nuclear systems, and general needs related to these areas. The following are the conclusions and recommendations from the two days of discussions. In addition, specific comments from the discussions are included to provide amplification of the conclusions and recommendations.

Although the conclusions and recommendations are not in all cases a consensus, they are in every case the view of a large majority of the participants.

CONCLUSIONS AND RECOMMENDATIONS

Four types of radioactive materials were addressed by the working group: High Level Waste (HLW), Defense Wastes, Surplus Fissile Weapons Material, and Low Level Waste (LLW).

I. High Level Waste (HLW)

This radioactive material includes the most radioactive of the waste as well as some extremely long-lived materials. HLW includes commercial spent fuel, although there is not agreement that this is purely a waste, and several types of government material from nuclear weapons production, naval reactors, and research reactors.

Goals for 2010-2015:

1. The Yucca Mountain geologic repository will have received an NRC license to operate.
2. Agreement reached on what is interim storage, enabling DOE, states, and owners of nuclear power plants to develop plans for stored HLW.
3. Technologies developed that would reduce the required time for proof of containment in a repository.
4. Consistent with the Nuclear Waste Policy Act, title to all commercial spent nuclear fuel (SNF) transferred to DOE.
5. Operation of a pilot plant to do partitioning.
6. Proof of principle completed for transmutation approach for use in ATW program.
7. An integrated ATW demonstration facility under construction to use a 10 MW accelerator.
8. DOE active participant in an international cooperative organization to address what to do with commercial spent fuel.

Accomplishing these goals will require some new technologies and overcoming some existing barriers.

New Technologies Required:

1. Waste packaging for repositories:
   (a) Containers, with longer lifetimes before failure.
   (b) Methods to demonstrate the containment times required for the desired container performance.
2. Partitioning technologies:
   (a) At the front end, probably aqueous, with controls to prevent diversion of separated material usable in nuclear weapons and to reduce the production of secondary waste.
   (b) Technologies for bulk processing, for example, pyroprocessing.
3. Transmutation technologies, of which the most prominent is ATW.

Barriers (or Challenges):

1. The standards for disposal are not yet established.
2. International collaboration will be difficult because of commercial proprietary information and sensitive nuclear information.
3. Complex regulations governing disposition.

NE Responsibilities:

1. NE is responsible for development and implementation of technologies for waste materials for disposal . Thus, NE is concerned with partitioning, transmutation, and waste form, but not for the container or for emplacement into a repository.
2. NE will be responsible for the ATW program.

II. Defense Wastes

Transuranic (TRU) defense wastes are being emplaced in the WIPP facility in New Mexico. There remain a large amount of other defense wastes in tanks, in fuel pools, in other storage, and in facilities to be decommissioned.

Goals for 2010-2015:

1. Program developed to dispose of Navy SNF, taking into consideration it includes highly enriched uranium (HEU).
2. Remove the dissolved radionuclides from tanks at Savannah River.
3. Remove all radioactive materials from and clean up the Hanford K basins.
4. Technologies developed to remove more effectively and completely all the radioactive materials from all waste tanks.
5. Implement monitoring systems at all appropriate DOE sites to identify the extent and the movement of sub-surface contamination.
6. Remove all SNF from Hanford storage basins and select treatment process(es) for disposal.
7. Develop plans to handle all defense HLW, including those currently without defined disposition paths, i.e., that HLW currently "without a home".
8. Implement a comprehensive inventory system that includes all forms of defense wastes, using consistent methodologies and having reconciled records.

Technologies required:

1. Because significant amounts of radioactive materials from nuclear weapons production processes have caused subsurface contamination, technologies are needed to immobilize wastes in deep subsurface regions.
2. Treatment processes to enable disposal of the damaged, corroded, and leaking SNF at Hanford.

NE Responsibilities:

NE does not have responsibility for defense wastes, but should offer technical assistance and propose any pertinent technologies developed in NE programs

III. Surplus fissile weapons materials disposition

As part of the programs to reduce the nuclear arsenals of the United States and Russia, substantial amounts of HEU and weapons-grade plutonium are being recovered from dismantled weapons. The HEU can be blended with depleted uranium to produce low enriched uranium to use in making fuel for nuclear reactors. The plutonium poses more difficult problems. The US and Russia have agreed to pursue a dual-track, or hybrid, approach in which two approaches are examined for plutonium disposal: immobilization and use in MOX fuel. There also is a collaborative effort with Russia and France, sponsored by DOE-MD, to develop a gas-cooled reactor to burn Russian weapons plutonium.

Goal for 2010-2015:

Dual track disposition program underway in the United States and a similar program underway in Russia.

NE Responsibilities:

1. NE should be involved in oversight of the programs to manufacture and review the performance of the MOX fuel and in the performance of the reactors to be used for the MOX program.
2. NE should follow the development of the Russian gas-cooled plutonium-burning reactor.
3. NE should examine whether the materials from the dismantled weapons have uses in research.

IV. Low-level Waste (LLW)

After more than an hour of discussion, the participants did not come to a conclusion as to whom is responsible for addressing the LLW issues. However, there was agreement that these issues needed to be addressed.

Goals for 2010-2015:

1. Reconsider what is defined to be LLW by removing high-activity waste from inclusion and considering excluding materials currently included at the lower limit.
2. Complete analyses of technologies that might provide solutions to LLW disposal problems.

Technologies required:

Waste minimization technologies.

In a lengthy discussion, some participants argued that technologies to separate LLW constituents could reduce the hazards associated with LLW sites and make such sites acceptable to the public. Other participants strongly disagreed.

NE Responsibilities:

NE should lead DOE efforts toward proposing solutions to LLW disposal problems.

V. Space Nuclear Systems

DOE has provided nuclear power systems for many space missions, including power generators for the recent Cassini mission and heaters for both Cassini and Mars Pathfinder missions. However, as NASA begins to plan more ambitious missions, it is useful to assess the potential application of a broader range of nuclear energy sources for non-military space missions.

General goals for space nuclear power systems in 2010-2015

1. Establish a DOE policy to support space nuclear power and propulsion systems.
2. To support this space policy, establish a base technology development program which includes:
   a) Development of advanced fuels.
   b) Development of high-temperature, light-weight materials.
   c) High-efficiency low-mass heat radiators.
   d) I&C systems.
   e) Power conversion systems
   f) Improved safety of systems..
   g) A range of radioisotope systems with greater efficiency.
   h) Development of protective coating materials and techniques for fuels, structural components, and nozzle throat.
   i) Light weight radiation resistant moderators
   j) High temperature turbine to operate at NTR outlet temperatures in a radiation field.

Goals for radioisotope power systems for 2010-2015:

1. Double the efficiency of current power system(s) with a range of technologies.
2. Establish an assured supply of Pu-238.
3. Provide radioisotope systems to meet a wider range of power levels.

Goals for space reactors in 2010-2015:

1. Demonstrate a flight-qualified fission system (5 - 50 kWe) suitable for power and nuclear electric propulsion (NEP).
2. Demonstrate the performance of a nuclear thermal rocket (NTR) fuel element (minimum of one) with characteristics of 5-30 MW/l power density and 3000 K outlet temperature.
3. Plan for full-up testing capability for an NTR.

Space reactor technologies required:

Fuels, materials (high temperature/light weight), shielding, core cooling technologies/components (e.g., thermal-hydraulics, heat pipes, pump, compressor), safety devices/analyses, energy conversion technologies, radiator/heat removal systems.
NEP technology selected to maximize performance, minimize weight, and maximize energy conversion, recognizing it may be necessary for trade-offs among these criteria.

Barriers to space reactors:

1. Public acceptance of putting nuclear systems in space. The controversy over the Cassini mission demonstrated the opposition.
2. Cost of a space nuclear system may be prohibitive.
3. To accomplish full-up testing may require building a new reactor, with both public acceptance and cost major challenges.

Submitted comment: an NTR development could test single fuel elements in a suitable test reactor (initially in TREAT, and eventually in a new test reactor). This test would primarily validate the elements mechanical design for prototypic values of temperature, temperature gradients, pressure, and flow rate. In parallel with this test an integrated engine test (including everything except the reactor) could validate the simultaneous operation of the turbo-pump assembly, thrust vector control, propellant management system, nozzle cooling flow control, etc. on a stand in which the reactor response is added by a simulator. Similar techniques are used in the aerospace industry to test systems for new aircraft (planes or missiles) prior to doing a full flight test. This approach would be less expensive, and would not be “full-up” . The final flight test could be done in space.

VI. General Needs

A department-wide need is for integration across DOE of planning and programs for issues related to nuclear energy.

An NE need is to increase teaming with international organizations and with universities.

VII. Some facility requirements

Although this workshop did not focus on facility requirements, participants in this session did identify some facility requirements as part of the discussions on the waste and space issues.

1. Facilities for steady state (fast spectrum) and transient irradiation testing to be used for both ATW and space programs. A very high flux reactor facility will be required for full-up testing of a prototype NTR fuel element.
2. Hot cell facilities for remote characterization of irradiated fuels and materials and radioactive waste materials. These would be useful for ATW, HLW, and space programs.
3. Accelerator and spallation target facilities for the ATW program.
4. Facilities for proof-of-principle testing, including pilot-scale fuel processing for the ATW concept.
5. A demonstration plant for an ATW system.
6. Infrastructure for Pu-238 supply.
7. Glovebox and laboratory facilities for technology development employing actinides.
8. Test reactor to simulate NTR power density and mission profile with an appropriate test position for testing single fuel elements of different design. This reactor could also be used to test the next generation steady state source reactor and isotope production reactor elements.

VIII. Education

This workshop did not address education explicitly, although the topic came up several times in the discussions in this session. One theme was the need for education in nuclear-related environmental issues, for example, establishing nuclear environmental engineering as a discipline. The participants recommended a goal of DOE working with universities to establish curricula to educate students in nuclear environmental technology and issues.

The participants recommended that each NE program allocate at least 2 % of the funds for universities and education.

SOME ***INDIVIDUAL*** COMMENTS: These are NOT consensus statements. They are individual statements included to provide more background for those not at the meeting.

High Level Waste (HLW):

The group expressed the desire for DOE to better integrate its offices for addressing waste issues. There are several offices with some responsibilities, but little apparent coordination among these offices.

Focus on a two-prong approach: develop ATW and aim for a shorter time period requirement for a repository license.

There is a close parallel between commercial nuclear waste and weapons legacy waste.

Spent fuel is not waste. There is a good amount of useful isotopes in SNF, e.g., Pu-238.

Look at alternatives to transmutation, such as an improved waste package. The current OCRWM waste package is designed for 300-1000 years.

DOE should have a transparent and reassuring monitoring system to use with subsurface radioactivity at places like Hanford. Putting a vadose zone monitoring system in is feasible and is part of the EMSP (environmental management science program).

Reprocessing/recycling/processing:

Broad agreement that the implicit/explicit ban on reprocessing should be lifted. The terminology is sensitive. Perhaps better to use recycling or conditioning instead of reprocessing.

Removal of the ban on reprocessing would allow the U.S. to once again participate in international reprocessing technology debates.

It is a mistake not to reprocess SNF. Other countries have not abandoned this option. Effort should be put on proliferation resistant means of handling the SNF.

Conditioning of the SNF to remove the "bad actors" would make it easier to get waste into a repository.

Partitioning of troublesome radionuclides allows for economical packaging using robust forms and packages.

Waste management and systems such as ATW should be viewed as part of a larger context that includes energy production in the next century. Recycle will be a necessary part of the global energy supply, so that the U.S. needs to get its story straight. This would be possible within a proliferation-resistant scheme.

PUREX-type facilities have led to the largest environmental impacts of nuclear facilities and the world inventory of separated plutonium is a major proliferation concern.

If the goal is a deep reduction in the number of nuclear weapons, then reprocessing plants operated by governments, which build stockpiles of separated plutonium, are impediments to reductions of weapons-usable materials. Commercial plants such as THORP and La Hague legitimize national efforts, e.g., Russian, to separate weapons-usable materials.

Yucca Mountain:

YM can be a safe interim storage site.

Any YM license likely will be an interim license. Congress may not be willing to force Nevada to accept HLW, so an ATW system could be an enabling program for YM.
An alternative to Yucca Mountain (YM) should be pursued. This does not require throwing away YM or postponing it until an ATW system is ready. There is a great benefit to getting the first spent fuel assemblies into YM, to show that the waste problem can be solved.

Two approaches could be pursued to address the large and growing inventory of SNF: (1) abandon YM and strive to produce waste that does not need geologic disposal; (2) pursue innovative waste techniques in parallel with YM.

ATW/Transmutation:

Reactor transmutation of waste might be an interesting concept and could be more immediate than ATW. Think of other systems, such as IFR (integral fast reactor) or advanced systems that might be deployed with an ATW system. Even future advanced reactor systems may require an ATW deployment, e.g., one ATW per hundred IFRs, to produce a "clean" waste stream.

Submitted comment: Although there is clearly merit in looking at reactor-based transmutation, there is no reason to believe reactors could be deployed more quickly than ATW. Of the three major technology components in ATW, the accelerator is the easiest and least time-consuming. Much more work is needed for the separations and the transmuter (the part that resembles a reactor). The correct justification for a reactor option is cost, since the accelerator probably adds about 15% to the cost of the system. However, one may need to have the accelerator to safely run on the waste-based fuel. If the fuel has nasty safety characteristics, one may be better off to absorb the cost of the accelerator rather than waste many years trying to license a facility.

Concerns about efficacy or potential of success of transmutation include the required reduction in bulk to make the system worthwhile, the energy required to operate the system, proliferation concerns with the reprocessing stage, and the actinides are not the radionuclides that lead to potential exposures from a repository.

Disagreement with these concerns included that the energy requirement will be met by the ATW system and that non-actinide isotopes, the major concern, would be addressed.

ATW would not be required if nuclear power is not supported. Others disagreed on grounds of waste disposal.

Materials disposition:

Recommend termination of the program to assist Russia in developing an HTGR for Pu disposition. This comment had little support among the other participants.

The proliferation risk today is in stockpiles of assembled weapons and assembled components. Efforts should be addressed toward reducing those risks, rather than on actinides in SNF.

A standard definition of proliferation resistance is needed. Is the "spent fuel standard" acceptable?

Does the United States worry too much about proliferation resistance of waste forms if other nations do not?

Low Level Waste:

The GAO has stated that LLW compacts have not become a successful answer to handling LLW.

Resolving what to do with LLW will be important for continued operation of power reactors and use of medical isotopes.

Should perform a system study of LLW options.

Should do research on radiation safety engineering and health effects of low-level exposure.

DOE should issue guidelines for exposure thresholds.

Space reactors:

Space nuclear power can be very attractive to students.

U-233 would allow a smaller space reactor core. All the U-233 we have should be retained for future space use.

Space reactor programs will have spin-offs for land-based systems.

Space programs will engender excitement in young people.

Space nuclear propulsion is a wonderful fit with the NE mission.

NASA will require nuclear propulsion for a real Mars mission.

The time constant for developing a space nuclear reactor is longer than the mission lifetime, so an ongoing base technology program is needed.

A joint program with Russia would be sensible.

Space nuclear R&D activities should understand that the biggest problem is the cost of development.

The first space nuclear system put up must be clean, safe, simple, and fool-proof to insure success.

NASA should be able to define needs. At the moment, DOE has no specific requirements for the first unit.

The first NEP system should be safe, economic - affordable with optimization with other requirements --, ground-tested, and simple.

The second NTR development will require high power density testing capability (10 e16 n/cm2/sec - TREAT -like capability) and capability for full-up testing.

Perhaps the NTR could be built in a tunnel at the NTS (nuclear test site in Nevada).

It would be best to have a system ready for deployment by 2010.

It will be necessary to use enriched uranium to get a low-weight reactor.

Maintain a technology base program for space nuclear power that would be independent of specific mission requirements. This would require a public commitment to support such a program for when the technology is needed.

Need to explain what is meant by "available". The ALWR has a set of drawings but is hardly available. Need to have hardware, infrastructure that is required to build a system, and be ready for launch to truly have the system available.

RTGs:

RTGs will continue to have their place in space use, but an additional Pu-238 supply will be required.

Some participants were concerned about relying on Russian supplies for Pu-238. The US might be supporting a production scheme that is counter to US environmental and proliferation goals.

Increasing the conversion efficiency will reduce the Pu-238 requirements.

Education:

There is a need to maintain the national infrastructure for nuclear engineering education.

Nuclear engineering needs exciting programs to attract the best and brightest students. ATW won't do it.

NE is getting better at competitive programs, such as NERI, but is not as good at collaborative programs with universities.

Appendix B

Working Group Report on – Medical Isotopes and Industrial Application

Nuclear Energy Research Advisory Committee

Subcommittee for Long Term Planning for Nuclear Energy Research

Summary Report
Medical and Industrial Isotope Applications Working Group

October 18-20, 1999 Workshop

Medical and Industrial Isotope Applications Working Group

The NERAC Subcommittee for Long-Term Planning for Nuclear Energy Research and Development conducted a workshop on October 18-20, 1999 in Chicago, IL. This record captures the discussion of a working group on Medical and Industrial Isotope Applications

Subcommittee Charge

The NERAC Subcommittee for Long Term Planning charge began with the following list of key questions:

- What changes should be made to DOE-NE's mission?
- What DOE-NE nuclear energy mission and objectives does this working group's R&D topic area support?
- What should the long-term role of the Department of Energy be in conducting nuclear energy R&D in this topic area?
- What specific R&D (subtopics) should the Department's Nuclear Energy Program focus on over the next decade? Identify any significant drivers for this needed R&D.
- What nuclear energy R&D will be conducted in this broad topic area outside of any DOE involvement?
- What are the challenges or barriers hindering R&D in this topic?
- What should be the order of priorities of these R&D efforts? [Note: While this question was initially posed, it was decided that the breakout groups would not attempt prioritization]

Working Group Discussions

Working group discussions focused on the following items:

- Scope and definition of "medical and industrial applications"
- DOE's recommended mission in this area, challenges in accomplishing this mission, and a recommended long-term vision
- The objectives it would have to pursue to achieve the vision
- The actions that should be considered to accomplish each objective.
- Linkages of the subject area of this working group to higher-level DOE planning documents

Each of these items is elaborated in the following sections.

Scope

The working group decided that the scope of DOE in this topic area is, *"all isotope and radiation science and technology research, development and applications."*

The scope excludes special-use isotopes such as Pu-238, which are considered by other workshops. Note: The term, "isotopes" is inclusive of stable and radioactive isotopes, unless it is specifically called out as, "stable isotopes" or "radioisotopes." Also included are radiation sources such as accelerators and beams.

Medical and Industrial Isotope Applications Working Group

Mission, Challenges, and Vision

Within the above scope, DOE's *mission* is to lead efforts to use isotopes and radiation to improve the quality of life and economic competitiveness in the U.S.

Major *challenges* to accomplishing this mission were identified as:

- Institutional complexity: Isotopes involves multiple elements of DOE, other Federal agencies, multiple DOE contractors, multiple universities, the private sector, important international players, Federal regulators, and state regulators.
- Economics and benefits not easily measured: The economics of isotopes are not easy to measure because governmental accounting practices are fundamentally different than commercial practices, investment in isotopes comes from multiple sources that are difficult to track, isotope research and production involves multiple use facilities leading to uncertainties in allocation of costs, and some governments subsidize isotope production in use in unknowable ways.
- No central leadership: Despite the widespread believe that use of isotopes is beneficial and the rapid increase in such use, there is no central coordination or leadership of isotope research and production.
- Public perception: Irrespective of the acceptance and growth of isotope use in many medical applications, most of the public still perceives the risks from radiation to be greater than the actuality or the benefits in other applications (e.g., food sterlization). Such perceptions challenge the reliable deployment of isotope uses.
- Maintaining technical expertise: Expertise concerning research, production, and utilization of isotopes is increasingly difficult to maintain. In part, isotope-related areas are not as attractive to new students as other technical fields (e.g., computers) because the latter offers better financial rewards and a better public image. In addititION, reductions in financial support for education and related facilities contributes to the decline.
- Deteriorating infrastructure: The facilities (reactors, hot cells, accelerators) used for education, research, and production concerning isotopes and radiation is generally old and reaching the point where maintenance costs are increasing. Superimposed on this, reductions in funding have resulted in some facilities having to be closed, sometimes without consideration of whether it is the best facility to be closed. The absence of central leadership precludes reasoned decision-making in this regard, which is exacerbated by the international dimension.

Given the above mission and the challenges in accomplishing it, the working group stated the following as the desired long-term vision for DOE's isotope and radiation program:

> The DOE is the leader of an enduring, cost-effective isotopes and radiation program with visible public benefits.

Medical and Industrial Isotope Applications Working Group

Objectives

In order to achieve a more specific focus, four major objectives were identified by the working group and are discussed below. Considerations related to international collaboration and facilities were considered under each objective.

Objective 1 -- Support Isotope Research, Development, and Demonstration: Establish a broadened portfolio appropriately balancing RD&D in medical, industrial, life sciences, environmental, agricultural and food safety research, and applications of isotopes and radiation.

Objective 2 -- Production and Inventory: Establish a reliable production, inventory, and irradiation system fully integrated among laboratories, universities, industry, and international isotope producers and/or radiation sources.

Objective 3 B Fostering Applications: Foster implementation of technologies using isotopes and radiation.

Objective 4 B Education: Maintain expertise and build interest in isotopes and radiation applications through a broad-based education program.

Supporting Actions

For each objective the working group used a round-table nominal group technique to develop specific actions that should be considered to accomplish each objective. The results were grouped into subtopics where there were an extensive number of activities, and described in the following sections.

Objective 1 B Support RD&D

New R&D for Applications

1. Conduct R&D on radioisotope delivery systems (such as brachytherapy seeds, etc.)
2. Conduct R&D on new isotopes for microelectronic devices (such as on-chip power supplies, sensor activation, etc.)
3. Conduct R&D on radiation-induced or Benhanced reactions to improve the efficiency or yield of industrial processes.
4. Conduct R&D to reduce radioactive waste streams through radioisotope replacement in applications (such as check sources, etc.)
5. Conduct R&D on non-destructive assay techniques.
6. Conduct R&D on non-destructive evaluation techniques.
7. Conduct R&D on radiation and/or radiation-based detectors, instrumentation and software.

8. Conduct R&D on dosimetry (such as dosimetry for novel beams, high-energy betas, neutrons, etc.)
9. Conduct R&D on regulatory and policy framework for use of isotopes in previously unregulated areas

R&D for Production and Processing

10. Conduct R&D on the production of new, diverse isotopes, as well as higher quality isotopes.
11. Conduct R&D on low-cost separation technologies for both front- and back-end application on the production process.
12. Conduct R&D for new radiation sources (such as accelerators for medical and industrial use, upgrading of existing facilities to meet new applications, equipment for food irradiation, etc.)
13. Conduct R&D on stable isotope production systems.
14. Conduct R&D to create uses for radioactive wastes. Evaluate spent nuclear fuel as a source of isotopes.
15. Conduct R&D on the production of novel isotopes with spallation sources.
16. Conduct R&D to improve the quality of nuclear data (such as cross sections, gamma energy spectra, emission probabilities, branching ratios, etc.)

Radiation Safety R&D

17. Conduct R&D to increase radiation safety for patients and/or workers through radioisotope replacement in therapies and applications.
18. Conduct R&D to improve the radiation safety of radioisotope production and radiation beam facilities (such as automating radiochemistry processes, improving operations or facility design, etc.)
19. Conduct R&D on sealed source and packaging technology.
20. Conduct R&D on radiation health effects, especially low-levels of radiation.

Organizing, Planning and Funding R&D

21. Decouple research and production funding to assure a more stable research funding level.
22. Lead and be a focal point for isotope and radiation technology.
23. Support a balanced R&D portfolio with segments for medicine, industry, agriculture, life sciences, environmental, etc.
24. Increase the involvement of university research reactors in R&D.
25. Develop a new generation of isotopes and radiation experts.
26. Create and facilitate a production Users Group composed of isotope researchers and users (such as NIH researchers, pharmaceutical manufacturers, etc.)
27. Create analogs to the Advanced Nuclear Medicine Initiative program in the areas of industrial and other applications.

28. Provide direct, peer-reviewed grants to researchers, with awards based solely on merit. Create grants for researchers to use DOE facilities.
29. Sponsor and conduct an ANS Topical meeting on isotopes and radiation R&D.
30. Convene brainstorming sessions with non-industry participants on innovative uses of isotopes and radiation.

<u>Objective 2 B Production and Inventory</u>

Production

1. Produce needed isotope “orphans” on a long-term basis. The term, “orphans” refers to isotopes that will probably never become commercially viable, yet have beneficial application.
2. Outsource production to university research reactors whenever possible.
3. Conduct an integrated comprehensive assessment of current isotope production systems. View the national laboratory, university and commercial sectors as an integrated production system.
4. Build new, dedicated isotope production capability.
5. Upgrade or modify existing facilities to meet changing demands.
6. Establish key partnerships with producers of isotopes.
7. Identify and evaluate key facilities for use by researchers.
8. Evaluate a policy to achieve domestic self-sufficiency for selected isotopes.
9. Establish or maintain effective regional production and distribution of short-lived radioisotopes.
10. Study production facility reliability, and establish programs to improve reliability.
11. Establish an appropriately sized, flexible facility for producing enriched isotopes (specifically including radioactive).
12. Maintain and enhance isotope production and radiation source infrastructures.
13. Coordinate international sources of isotopes for domestic needs.

Marketing and Distribution

14. Provide low-cost (or at least below-cost) isotopes to researchers.
15. Establish a single point-of-contact for isotope and radiation source availability.
16. Establish good business practices customized for individual customer groups.
17. Create and facilitate an Advisory Group composed of isotope researchers.
18. Develop a realistic cost/pricing method for production of isotopes and use of facilities.
19. Study and update yearly demand forecasts for isotopes, and review production goals.

Standards

20. Support participation in the development of national standards (such as ANSI or US Pharmacopeia standards for purity, use, disposal, etc.)
21. Produce unique physical standards not provided by NIST.
22. Act to assure the traceability of DOE-produced standards to NIST.

Inventories

23. Preserve and maintain potentially useful isotope inventories (both stable and radioactive).
24. Catalog and publicize production and inventory of isotopes and sources, as well as facilities and staff, for existing and potential users.
25. Guarantee the availability and reliability of isotopes.

<u>Objective 3: Fostering Applications</u>

1. Encourage collaborative efforts with industry that can afford improvements in commercial technology (such as CRADAs or sponsored research).
2. Study the transportation, regulatory issues and technology associated with isotope delivery.
3. Establish a demonstration facility for pilot applications of isotope-based applications (such as waste treatment, processing, etc.)
4. Sponsor public advertisements.
5. Supply isotopes at no cost for demonstration of new, proposed uses.
6. Provide technical support for new, innovative isotope and radiation applications.
7. Create and encourage User Groups for isotopes, and sponsor workshops, seminars, etc.
8. Establish a clear policy statement on isotopes and radiation, to the effect that they have a great benefit and that DOE will foster their use.
9. Facilitate and fund university, national laboratory and commercial collaboration to use isotopes and radiation sources.
10. Make an annual award to recognize important and innovative research and applications of isotopes and radiation sources.
11. Develop a systematic method for evaluation, and perform cost/benefit analyses to guide isotope deployment decisions.
12. Provide leadership and seek to enhance collaboration with other government agencies.
13. Monitor commercial, government and university sectors for potential improvements and brainstorm new applications of isotopes and radiation sources.

14. Sponsor high-visibility experiments on the International Space Station.
15. Sponsor an annual conference on the uses of isotopes and radiation.
16. Establish regulatory assistance for potential users.
17. Lower the barriers for first-time users.

<u>Objective 4 B Education</u>

1. Continue to provide information on the beneficial uses of isotopes and radiation.
2. Publicize R&D needs for isotopes and radiation.
3. Provide educational seminars to Congressional members and staff.
4. Organize and fund specialized workshops and visits to DOE facilities for potential researchers and users, including students.
5. Establish national laboratory and university staff sabbaticals, etc.
6. Sponsor summer programs for students at the national laboratories
7. Create an ANS Student Design Competition on isotopes and radiation sources and applications.
8. Sponsor a funded chair for Isotopes and Radiation at a university.
9. Establish a Speaker's Bureau to reach the public, potential users and universities.
10. Establish short courses and workshops for industry.
11. Write a paper for *MIT Technology Review* (or other magazines) on the use of isotopes.

Linkages to Other Plans

<u>DOE Strategic Plan: Sciences and Technology</u>

Strategic Goal: Deliver the scientific understanding and technological innovations that are critical to the success of DOE's mission and the Nation's science base.

Objective: Deliver leading-edge technologies that are critical to the DOE Mission and the Nation.

Strategy: Develop the technologies required to meet DOE's energy, national security, and environmental quality goals

Supply quality, stable, and radioactive isotopes for industrial, research and medical applications that continues to meet customers specifications and maintain 95% on-time deliveries in FY 1998 and beyond.

<u>DOE/NE Vision: Benefits of nuclear technology to our society can and should be expanded.</u>

R&D Objective: Conduct medical research to broaden and improve the application, type, and effectiveness of nuclear medical therapies.

Objective: Interact with foreign researchers and promote cooperative R&D programs with foreign governments in order to share the cost and expand expertise.

Provide assistance to college nuclear engineering programs to foster academic excellence and improve nuclear research and training facilities.

Appendix C

Working Group Report on – Materials and Corrosion R&D

Nuclear Energy Research Advisory Committee

Subcommittee for Long Term Planning for Nuclear Energy Research

Summary Report
Materials And Corrosion Research Needs Working Group
October 18-20, 1999 Workshop

DOE LONG-TERM NUCLEAR ENERGY R&D PLAN
MATERIALS AND CORROSION RESEARCH NEEDS

INTRODUCTION

Safer, more environmentally benign, longer operating, better performing and economically superior nuclear fission power reactors and radioactive waste containment systems, and more generally optimization of the entire nuclear fuel cycle, will require improvements in materials and corrosion prevention. The design and nature of the next generation nuclear power systems are still unknown. Thus, the materials and operating requirements (temperature, coolant, etc.) are not well defined. It is eminently clear, however, that improved radiation and corrosion resistance will be needed. Similar unknowns exist for the nuclear fuel cycle; for example, will spent nuclear fuel continue to be considered a preferred waste form or will alternative concepts, such as accelerated transmutation of waste (ATW) be implemented. Since new science or new materials often take as long as 20 years to be implemented into new technology, it is imperative that long-term research and development on improved materials, materials performance, and corrosion be undertaken in advance of new designs.

The materials science paradigm, in which synthesis and processing is used to manipulate materials' microstructures in order to improve properties, offers tremendous potential for stimulating innovation and driving progress in many areas of nuclear technology. In their report to the President dated November, 1997, and entitled "Federal Energy Research and Development for the Challenges of the Twenty-First Century", the President's Committee of Advisors on Science and Technology (PCAST) stated "The Federal Government's role is to ensure that long-term problems with nuclear power are addressed so that nuclear can become, if possible, a realistic and acceptable energy option, as well as a hedge in case renewables and efficiency cannot reach the performance levels and market share necessary to meet emission reduction targets." The long-term materials and corrosion research needs described below were formulated to meet the stated goal.

We have divided this report into sections that correspond to various long-term research topics in materials and corrosion. This classification does not imply that borders actually exist between these topics. Any research project that addresses long-term needs and opportunities for improved materials and corrosion prevention may indeed cut across any number of the topics that are identified below, and many of them are interrelated. As the following sections describe in greater detail, cutting-edge materials science and engineering research is a critical need in each of these topics, and there is substantial opportunity for consequential technological pay-off and scientific excitement in all of them.

IRRADIATION ASSISTED STRESS CORROSION CRACKING AND AQUEOUS CORROSION

There is insufficient fundamental understanding of radiation effects on alloy behavior at LWR temperatures and dose-rates to reliably predict component properties and thus mitigate service failures. A recent assessment of the radiation-induced material changes that are believed to influence LWR core component cracking is available [1]. This report also identified long-term research needed to elucidate the underlying failure mechanisms. Our discussion on this topic largely follows from that review.

A growing concern for electric power utilities worldwide has been the degradation of core components in nuclear power reactors, which currently generate ~17% of the world's electric power. Failures have occurred after many years of service in boiling water reactor (BWR) core components and, to a lesser extent, in pressurized water reactor (PWR) components. These failures occurred in stainless iron- and nickel-base alloys exposed to sufficiently high levels of neutron irradiation in the reactor coolant environment. This environment is typically oxygenated or hydrogenated water at about 290^{O}C, but the temperature can range from 270^{O}C to 370^{O}C in specific locations. The coolant chemistries can become more aggressive in crevice situations, where component failures are often observed. Since cracking susceptibility requires a combination of radiation, stress and a corrosive environment, the failure mechanism has been termed irradiation assisted stress corrosion cracking (IASCC). Until recently, the components affected have been either relatively small (bolts, springs, etc.) or designed for replacement (control blades, instrumentation, tubes, etc.), but more structurally significant components such as top guides and core shrouds have also been degraded. Because testing of irradiated materials is difficult and expensive, it is highly unlikely that a purely empirical approach will provide an adequate understanding of IASCC behavior.

Recent reviews [2 - 7] have been published which describe much of the current knowledge related to IASCC service experience and laboratory investigations. These reviews highlight the limited amount of controlled experimentation that exists on well characterized materials. Moreover, there are inherent difficulties in quantifying SCC response that preclude direct comparisons between radiation-induced changes and cracking behavior. This lack of critical experimentation underscores the necessity that a scientific approach be pursued to acquire a fundamental mechanistic understanding of IASCC.

Advances in IASCC understanding require research focused in radiation materials science, and more generally, on the fundamentals of grain boundary behavior, corrosion, localized deformation and fracture. Radiation materials science begins with the atomic displacement processes that drive microstructural changes. However, linking these changes to environmental cracking requires that underlying principles be elucidated for both irradiated and unirradiated conditions. A detailed discussion of the research needed to improve the mechanistic understanding of radiation-induced material changes and IASCC of LWR core components is presented in [1]. This underpinning knowledge is essential for the continued effective operation of current LWRs and for the design of optimized nuclear power systems.

Important progress has been made over the last decade to identify specific parameters that promote IASCC susceptibility. It is now clear that persistent radiation-induced changes control the behavior. Application of high-resolution characterization techniques to IASCC in LWR-irradiated materials has clarified many issues related to microstructural and microchemical evolution during irradiation.

However, nearly all measurements have been performed on uncontrolled commercial stainless steel heats without any systematic variation of irradiation or material parameters, especially composition.

Hence, there is a paramount need for mechanistically driven, single-variable experiments to elucidate radiation-induced material changes and their effects on IASCC. The use of alloy compositions and irradiation conditions much broader in scope than the standard LWR component experience is crucial to understanding IASCC behavior and uncovering opportunities for improved materials. Optimal compositions and conditions must be selected based on a fundamental understanding of radiation-induced changes. Prior experience [8,9] in establishing the mechanisms and material variables controlling void swelling and in the development of swelling-resistant materials provides excellent examples of how advances in fundamental understanding can lead to important practical advances.

Reference [1] identifies and elaborates on the following research needs in radiation materials science: (1) defect production and clustering in multi-component materials, (2) multi-scale microstructural modeling , (3) transient evolution of microstructure, and (4) defect/solute interactions at grain boundaries. The microstructural defects that form and the changes in grain boundary composition that occur are now qualitatively well understood. However, accurate prediction of microstructures, microchemistries and mechanical property changes in complex stainless alloys during irradiation at LWR temperatures is not currently possible. Mechanistic understanding of these radiation-induced changes in commercial alloys is of paramount importance to predict and mitigate intragranular cracking that occurs in service. The proposed research is needed to define microstructural and microchemical evolution at intermediate temperatures and dose rates pertinent to LWRs where transient effects often dominate.

It must, however, be recognized that advances in radiation materials science alone are not expected to produce a mechanistic understanding of IASCC. The radiation-induced material changes must be linked to known (and perhaps yet unknown) structure-property relationships. A continuum must exist between the behavior (e.g., grain boundary properties, corrosion reactions, deformation and fracture) of unirradiated materials and that under irradiation. The continuum approach recognizes that the irradiated alloy properties are not unique. The role of irradiation is simply to perturb the microstructure and microchemistry, and thus to change the threshold for intragranular cracking. The crystal structure, base alloy composition and exposure to stress are the same for irradiated and unirradiated alloys, although critical details in the material's condition differ. A consistent interpretation of material response must be developed that satisfies our mechanistic understanding of both irradiated and non-irradiated behavior.

Thus in addition to the research in radiation materials science described above, additional areas needed to understand IASCC include: (1) deformation and fracture, (2) grain boundary structure and properties, and (3) corrosion/electrochemistry in high-temperature water environments, including properties of the material/environment/oxide interface at the crack tip. Radiation impacts each of these areas, but the underlying mechanisms are common to irradiated and non-irradiated materials.

In addition to the corrosion issues directly linked with irradiation, related long-term research needs also exist in general corrosion phenomena including crevice corrosion and high temperature aqueous chemistry. Needs for improved understanding in corrosion include, but are not limited to, problems involving compatibility with water at relevant elevated temperatures, and stress-corrosion cracking (SCC) in general. A better understanding of the processes underlying SCC should permit the development and use of less expensive SCC resistant materials than those now in use, and may also reduce the dependence on expensive testing programs.

Crevice corrosion involves aggressive chemical environments in a localized region. It can occur both on macroscopic, e.g., in the region between a steam generator tube and the tube support plate, and on microscopic levels. Modeling and experimental research, including the development of instrumentation to measure the chemical environment within a crevice, would permit evaluation of critical parameters such as corrosion, and crack propagation rates, and help identify mitigative measures such as changes in environment, again reducing the dependence on difficult and expensive testing. Corrosion processes depend on the chemical reactions that occur between the environment and the materials of interest. Such chemical processes, including the formation of insoluble precipitate films, also play an important role in the development of crevice environments. Characterization of these reactions is critical for the development of predictive models for corrosion related-phenomena.

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REACTOR PRESSURE VESSEL EMBRITTLEMENT

The Department of Energy's Office of Nuclear Energy and Office of Basic Energy Sciences/Materials Sciences, along with the Nuclear Regulatory Commission and the Electric Power Research Institute jointly sponsored a Research Assistance Task Force (RATF) on reactor pressure vessel embrittlement which took place on 20 - 21 September 1999. The proceedings of this meeting have been published [1] in the form of a report that contains summaries of the deliberations of the meeting, along with the presentation materials of all the speakers. Below we summarize the findings and recommendations of this meeting.

Reactor pressure vessels (RPVs) are massive ferritic steel structures. In these materials there is a well known ductile-to-brittle transition temperature (DBTT). Above the DBTT the material fails in a ductile manner, and the fracture toughness is high. Below the DBTT the energy to cause fracture is low and failure is characterized as brittle based on fractographic characteristics. Irradiation causes the DBTT to shift upward, while simultaneously decreasing the upper shelf energy, i.e., the fracture toughness at temperatures above the DBTT. This area comprises a large field that spans materials science research and materials engineering in the support of light water reactor technology. In steels not tailored to be radiation resistant, the DBTT can reach hundreds of degrees C and the lowering of the upper shelf energy can be tens of percent, even at doses well below the end of life displacement damage level of ~0.01 dpa for RPVs. Of main concern is the possibility that with such large shifts, brittle behavior could be encountered near the temperature regime of normal reactor operation or shutdown. In addition to improving the material's behavior in response to this concern, a more precise knowledge of the in-service toughness of the RPV would have a substantial positive impact on the operation of existing power reactors. In particular, more precise knowledge can be expected to save in excess of $4 M per reactor by permitting less conservatism in cool-down and start-up procedures [2].

Materials research on the effects of impurities and alloying elements such as copper, nickel and phosphorous has resulted in substantial improvements in the performance of ferritic pressure vessel steels. By controlling alloying elements, the DBTT shift can be reduced several fold. However, the physical processes underlying these elemental effects are not understood on a mechanistic microstructural basis. Further improvements in performance beyond the considerable advances already achieved by traditional empirical metallurgical approaches will require advances in materials science research.

The needs for this research are: (1) to improve the economics and safety of operating reactors by reducing unnecessary conservatism in current reactor start-up and shut-down procedures. (2) to improve understanding of the connections between defects, microstructure and macroscopic mechanical properties, in order to formulate predictive models. (3) to obtain maximum benefit from current embrittlement surveillance programs. Although enormous amounts of data have been accumulated under actual operating conditions in numerous reactors on various steels in myriad conditions, without the purposeful control of variables that characterizes the materials science approach, it is difficult to obtain insight from these data into the basic mechanisms of embrittlement, and empirical correlations based upon such data inherently contain large uncertainties.

Testing of surveillance specimens does not address certain important issues, including:
(1) the substantial effect of flux attenuation through the vessel thickness. (2) the spatial variability of microstructure and properties over such large structures, (3) the validity of embrittlement correlations

and (4) characterization and behavioral effects of processing-induced banding and segregation. To address these issues requires obtaining and testing materials from decommissioned pressure vessels.

Similarly, there is a critical need to retain and preserve surveillance specimens. Even though the retention of irradiated but untested materials may no longer be required by regulations, these specimens are irreplaceable in terms of the time and operating conditions to which they have been exposed. It is also necessary to account for the fact that the irradiated material in a given surveillance specimen is generally not of precisely the same microstructure, chemical composition or defect state as nominally the same material at an arbitrary location within the massive pressure vessel structure.

The effects of very long irradiation times, i.e. $>10^5$ hours, require experiments and modeling that embrace (1) gathering and analysis of further statistical evidence for recent preliminary reports of increased embrittlement rates at long times. (2) assessment of the importance of long irradiation time-induced embrittlement, in view of possible extensions of reactor lifetimes to 60 or even 80 years. (3) development of reliable predictive models for behavior, based on understanding the mechanisms that are responsible for microstructural development, including the possible formation of late-blooming phases, and (4) understanding the interplay between long term thermal aging phenomena and long term radiation effects.

The mechanistic basis for mechanical behavior that led to the empirical success of the "master curve" approach needs to be better understood. The shift in fracture toughness transition temperature needs to be reliably modeled in a physically based approach that is rooted in microstructure and precipitate evolution. Thorough experimental characterization of the transition in fracture toughness is necessary over a wider range of materials and conditions. This includes the resolution of technical issues that are associated with the application of the master curve approach.

There is a strong need for detailed knowledge of the structure and composition of both the matrix defects and copper-containing precipitates that underlie embrittlement. The matter is complicated by the fact that there generally exists a wide range of precipitates and clusters, some of which are only loose correlations of atoms that do not fit the description of precipitates in the usual metallurgical sense. Knowledge of the degree of co-segregation of additional solutes, e.g., P, Mn, Ni, and Si, to these extended defects, as well as knowledge of their interactions with mobile dislocation segments, are also required before improved predictive models of irradiation-induced mechanical property changes can be constructed.

Molecular dynamics simulations of cascade production, as well as other atomic level calculations, which provide information over atomic distances and unprecedented small time scales (0 to 100 ps), currently suffer from inadequate interatomic potentials. Such potentials need to be developed. The integration of multi-scale approaches on theoretical and experimental levels needs further development. The modeling methodologies range from molecular dynamics simulations at the atomic scale to global defect reaction rate theory for predicting the evolution of microstructure and precipitation and the concomitant effects on properties [3]. The situation with embrittlement is more involved than with similar work on radiation-induced dimensional changes. In work on radiation induced swelling and creep, for example, the output of microstructure and precipitation predictions emerging from these methods is sufficient in principle to determine completely the swelling and creep behavior. However, for radiation induced embrittlement, the microstructural state, whose quantification by calculation is very demanding and presently achieved only in special cases, is merely a first phase in the determination of embrittlement. Once the microstructural state of the material has been reproduced by this type of modeling, further continuum dynamics methods need to be integrated for predicting deformation and fracture behavior of the material in its evolved microstructural state. In the development of such integrated multi-scale models, it is always crucial to "benchmark" computations and simulations against experimental measurements.

Some of the expectations for success of long term research on issues related to reactor pressure vessel embrittlement are: (1) further reductions in the ductile-to-brittle transition temperature at high neutron fluences, (2) reduction in excessive conservatism in reactor design and operating rules, and (3) understanding of the mechanisms of response of pressure vessel materials during annealing and re-embrittlement. In turn this will permit more reliable knowledge of vessel condition and more efficient reactor operation.

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MECHANISMS AND MODELING FOR THE DEGRADATION OF RADIOACTIVE WASTE PACKAGES

The nuclear waste package for interim storage or permanent disposal currently consists of spent nuclear fuel assemblies or other solid nuclear waste forms contained in metal canisters. The properties of the spent nuclear fuel, other solid nuclear waste forms, and the canister itself, may degrade in the presence of water or radiation damage from radionuclide decay [1,2,3]. The degradation processes due to corrosion and radiation damage must be understood well enough that extrapolations of waste package behavior can be made confidently over periods of at least ten thousand years. Public acceptance of nuclear power as an important energy source depends on developing acceptable solutions to the backend of the nuclear fuel cycle; scientifically-based and carefully engineered solutions are more likely to gain public acceptance. Other countries pursue strong research programs on all phases of the commercial nuclear fuel cycle, particularly materials science issues related to the reprocessing of spent nuclear fuel and development of waste forms and packages. Hence opportunities for international collaboration, and mutual benefit exist.

Spent nuclear fuel (SNF), which contains over 95% of the total radioactivity that requires geologic disposal, is the principal waste form in the United States. It is essentially restructured UO_2 with approximately 4 percent fission products and transuranium elements, such as Pu and Am. Although there has been considerable research on radiation effects in highly crystalline UO_2 and UO_2 fuel under reactor irradiation [2], the effects of self-radiation at ambient temperatures in restructured, highly-damaged UO_2 that may not be stoichiometric are not known. While UO_2 is highly radiation stable, the higher uranium oxide, U_3O_8, is one of the easiest materials to amorphize [4] under irradiation. Since very little is known about radiation effects in nonstoichiometric UO_2, there is need for research in this area. There is also still considerable work required to elucidate the corrosion processes and products of UO_2 for scenarios invoking canister failure. Under oxidizing conditions, such as will exist at Yucca Mountain, the corrosion products of UO_2 [5,6,7], mainly U(VI) hydrated phases, will form rather quickly (on a scale of hundreds of years once exposed to water vapor) and may become the principal host phases for transuranium elements and some of the fission products of concern (e.g., Se [8] and Tc [9]) . These U(VI) hydrated phases could therefore become the dominant source of actinides and other radionuclides released to the environment. The oxidative-corrosion process of this semiconductor material is also accelerated due to surface-dominated reactions with free radicals that result from radiolysis of water in contact with the fuel.

The metal containers that make up the waste package were originally proposed to consist of thick layers of corrosion resistant metals and were estimated to cost approximately $300,000 each. More complex designs (e.g., double layers) or exotic alloys are now under consideration to improve the corrosion resistance of the canisters, but the cost estimate per canister is greatly increased (approaching $1 million each). The large volume of current commercial spent nuclear fuel assemblies in the USA (approximately 35,000 metric tons) will require on the order of 10,000 such containers for a net cost estimate of up to $10 billion. An improved scientific understanding of the actual mechanisms and kinetics of degradation for canisters, SNF, new fuels and cladding, and other solid waste forms over geologic time periods would significantly reduce the large uncertainties in performance assessments, thereby reducing costs and risk to the public.

Storage concepts involving the partitioning of radionuclides into more durable waste forms, or into inert matrices for transmutation using accelerator-based neutron sources or nuclear reactors, appear promising. Recent studies [10, 11] suggest that actinides can be incorporated into radiation-resistant ceramics that demonstrate outstanding resistance to environmental degradation. While such results are encouraging, validation of these concepts and materials will require vigorous experimental programs and the sort of computer modeling described later in this report. Similarly, any decrease in the volume of spent nuclear fuel through transmutation, such as through the ATW (accelerator transmutation of wastes), will reduce the direct cost of disposal proportionately.

Internationally and in the USA there is a considerable focus on the fate of weapons Pu (approximately 100 metric tons); however, larger amounts of Pu are generated by commercial power production (approximately 70 metric tons per year world-wide). The present world inventory of Pu is greater than 1,300 metric tons, and the amount of separated Pu from reprocessing commercially generated spent nuclear fuel (outside the USA) is approximately equal to the amount of weapons grade Pu produced for the various national defense programs. As already noted, the partitioning of the actinides for immobilization or transmutation offers promising alternatives to the direct disposal of SNF. Greater involvement of USA scientists and expertise in the development of acceptable solutions to this international issue could increase public acceptance of the nuclear power option in the USA. A significant amount of scientific understanding is needed, particularly related to radiation effects and corrosion, on actinide-bearing solids that may be used as inert matrix fuels or eventual waste forms, as is being considered in Europe. Highly durable, radiation-resistant waste forms for actinides are desirable [10] and potentially attainable [11].

In the future, if the partitioning of radionuclides becomes part of a new nuclear fuel cycle, then highly durable and radiation-resistant materials can be utilized for immobilization of radionuclides, whether for disposal or transmutation. Under such circumstances, the waste forms or transmutation hosts themselves could be the primary containment systems for final deposition, limiting the need for expensive waste package containers. Research and development of new materials and reliable performance models need to be initiated far in advance of when they will be needed. Clearly, significant improvements in safety, reliability, and public acceptance of nuclear technology can be realized through the development and study of new materials and concepts.

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WELDING AND JOINING

Reliable welding and joining procedures are necessary for joining metals, ceramics, and dissimilar materials in general. This need pertains both to the construction of future reactor systems and for the on-line repair or refurbishment of aging existing ones.
Particular concerns include the welding repair of irradiated steels and corrosion resistant alloys, development of crack resistant filler metals for nickel based alloys and reliable joining of ceramic composites. Advancing new welding processes and developing new welding procedures can help prevent expensive power outages attributed to weld-related problems. Some of the recent areas for welding research in the nuclear power industry were highlighted in the EPRI (Electric Power Research Institute) Journal [1]. The following paragraphs are largely based on quotations from this article.

Weld failures are unavoidable and are a common cause of down time in fossil and nuclear energy plants. Day in and day out, metal parts are exposed to cycles of extreme temperatures and pressures, radiation, corrosion, and other factors that take their toll in the form of cracks, splits, ruptures, embrittlement, and pitting. As the U. S. power industry nurses its aging facilities where more than half of its nuclear plants are over 15 years old, welding is going to become an even hotter topic. Better welds can extend the lifetime of older components by decades and can save the industry billions of dollars. A good weld extends plant life, enhances safety and reliability, and cuts down on operation and maintenance costs. These benefits are especially important in nuclear plants, where a day of forced outage costs $300,000 to $750,000.

New welding technologies such as laser welding, underwater welding and temperbead repair welding make possible the ability to weld parts on-site, and sometimes in-situ, which greatly reduce the cost of weld repairs. In today's competitive business environment, in which it may be cheaper to maintain an old plant than build a new one, welding is a crucial aspect of plant management. It represents 10% of new construction costs and 20% of maintenance costs. In some cases welding may provide the only economically viable approach for avoiding a permanent plant shutdown.

Temperbead repair

Temperbead repair can be considered the innovation that has made the biggest impact on the industry. Many of the steels used for piping and pressure vessels must be given post-weld heat treatments (PWHT). This treatment softens or tempers the hardened material after a weld is performed and so relieves residual stress. It also allows the diffusion of hydrogen, which is introduced into the metal during welding and can cause cracking. But PWHT is time-consuming and expensive, especially when the components involved are large or when many treatments are necessary. In nuclear plants, it can take up to 12 hours for a component to reach the desired temperature, 1 to 3 hours to perform the treatment, and another 8 to 12 hours for cooling. Sometimes PWHT may not even be possible because of the size or configuration of the flawed part.

Temperbead welding performs the same function as conventional arc welding with PWHT, and its results can be equal or superior. In this process, welding beads are deposited in precisely controlled patterns, and each successive bead provides heat tempering for the layer directly below it. It is an especially valuable technique for the in-situ repair of large components, including pressure vessels and turbine casings, which have traditionally needed to be removed for repair off-site. Carbon steels and low-alloy steels can now be repaired without PWHT as long as the repair produces toughness properties comparable to those of the base metal.

Although major improvements have been made in temperbead repair welding over the past few years, more research and development is needed to extend, if possible, this technique to encompass higher chromium content steels such as the P91 materials. These materials are being used for new construction around the world due to their better strength-to-weight ratios and reduced overall costs. More importantly in the U.S., utilities are using the material for retrofits or replacement of aged piping or tubing. Temperbead technologies to allow utilities to replace piping/tubing would result in huge savings in terms of postweld heat treatment costs.

Laser welding

Advances in the field of laser welding have recently made possible the delivery of multi-kilowatts of NdYAG power through sub-millimeter diameter fiber optic laser delivery systems. These high power lasers provide excellent welding sources because of their high power density, their ability to be automated, and their ability to weld in remote locations. Since workers have the option of defocusing the beam over larger areas, lasers can also provide a means to enhance weld and material properties through localized heat treatment. Compared with conventional methods, automated laser welding is faster, requires less finishing and machining, and can repair damaged parts that once were considered hopeless. Other advantages of laser welding may include precision, minimal weld dilution and minimal heat affected zone sizes.

Lasers also have the ability to melt powdered filler metals for localized weld repair, cladding, and surface alloying. The ability to melt special powders allows welders to create complex mixtures appropriate for both the initial application and for the repair of ceramic thermal barrier coatings (TBCs). Structural type repairs of superalloy gas turbine blades are being studied to repair the high-stress regions of blade airfoils, and lasers are being looked at to develop repair alternatives for directionally solidified materials such as GTD-111.

The potential of lasers in power plant applications has only begun to be tapped. Perhaps the largest advantage of laser welding is in providing excellent opportunities for repairing components on site and in situ without having to open up the reactor. Such repairs can potentially avoid the high cost of extended period shutdowns. One of the big challenges for the laser welding industry will be in the development of higher average power laser systems that can be taken to the field. Higher power lasers would enable increased deposition rates for repairs of power plant components such as rotors and piping. Laser cladding, to combat corrosion/erosion of waterwalls and wear of valves, will also benefit from enhanced laser power. In addition to higher laser power, all on-site laser applications will benefit from the development of better techniques for automating laser welding repairs, which will cut welding costs and minimize the chance for human errors.

Underwater welding

In the nuclear power industry, underwater welding has recently been employed in repairing boiling water reactors. Although it is difficult for repair workers to go into a reactor because of radioactivity and access limitations, it is done under certain circumstances. It is safer for workers to perform such work underwater because water itself offers great protection from the radiation. This avoids the need for the extra shielding that is required when a reactor is drained. To avoid the problems associated with repair workers having to enter reactors, much underwater welding is automated. It is mainly used to make repairs inside the lower two-thirds of a reactor pressure vessel, which is inaccessible and radioactive, and to repair fuel storage pools.

Recent examples of core shroud cracking and the potential for degradation in other RPV components highlight the need for the development of specific repair technologies. Underwater welding technology developed for austenitic materials should be expanded to include irradiated materials. Highly irradiated materials (10^{24}n/m^2 or greater) contain a concentration of helium that can lead to underbead cracking and hot tearing of welds and heat affected zones. Empirical evidence suggests that low heat input, low dilution welding processes might provide good results. Several underwater options are available including flux-cored arc, plasma-arc, and laser welding techniques. Research directed towards improving the stability of arcs at water depths below 50 feet is required, and needs exist for developing new welding electrodes with improved wet weld characteristics. There are several needs for the successful development of irradiated welding technology, which include the identification and acquisition of suitable test materials, coordination of underwater facilities with hot labs, welding and testing of equipment, and assessment of "weldable" helium levels.

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NON-DESTRUCTIVE EVALUATION AND CONDITION MONITORING

Non-destructive evaluation (NDE) has two very critical functions in the production of nuclear energy. One of these functions is to provide the highest possible quality assurance for the components that comprise a reactor and for periodic inspections during outages. Improvements of this sort include both the detection and characterization of flaws and the characterization of the properties of the material in which they might reside. Regarding discrete flaws, decreasing the flaw size that can be reliably detected, increasing the ability to characterize and size those flaws (e.g. differentiating them from benign geometrical discontinuities, and developing techniques that can detect such flaws in parts of increasingly complex geometry (without the need to modify that geometry for the inspection), are all important issues. Improvements in the speed, accuracy, resolution and detectability limits of such techniques will lead to improvements in plant safety, operating efficiency and the safe lifetime of components. Quality assurance techniques also include the characterization of failure related properties of the material in which the flaws reside. Important targets include techniques to measure embrittlement and remaining fatigue life.

A second function of NDE is to provide continuous condition monitoring, i.e., in-situ or on-line early warning of possible impending or catastrophic component failure, including the ability to predict the remaining safe lifetime for a component. This implies that the sensor both give the requisite information (based on sound measurement principles) and that it be able to survive and function under the hostile environments that are seen by the component itself. Examples include irradiation, high temperatures, stress, and an aggressive or corrosive chemical environment. There are many opportunities here for long term research.

Ultrasonic, electromagnetic (especially eddy current) and radiographic techniques receive by far the most usage in the detection, characterization and sizing of flaws because of their ease of use in the challenging nuclear power plant environment. There are important opportunities for the development of improved signal processing procedures to better discriminate signals from background noise, for artificial intelligence techniques to discriminate between signals from flaws and those from benign geometrical discontinuities, and for inverse scattering techniques for determining the sizes of flaws. As a specific example, improved NDE techniques are needed to characterize flaws in steam generators, where it is very difficult to distinguish between harmful crack-like defects and innocuous inclusions. In order that these techniques provide the form of output most desirable from a life management perspective, it is highly desirable that they be conducted within a probabilistic format so that parameters such as probability of detection can be quantified.

There is considerable work to be done to develop algorithms that will produce probabilistic output. Early indications show that the use of physical models of the inspection process can play an important role in these developments. The detection of discrete flaws is often rendered quite difficult by the complexity of the surrounding geometry. A classical example is in the area of weldments, in which various geometrical complexities, e.g. offset, can produce signals that are difficult to distinguish from those produced by cracks. A less familiar problem is found in steam turbines, 30% of which suffer from stress-corrosion cracking at the blade to rotor attachment areas known as the steeple. NDE techniques are needed to permit inspection of these regions without having to remove the blades. An example of a possible solution would be a tomographic reconstruction using a form of energy sensitive to the corrosion products.

The measurement of failure related material properties is one of the “holy grails” of NDE whose solution would have tremendous impact [1,2]. For example, development of NDE techniques that can measure the degree of embrittlement of reactor pressure vessel steels caused by long time exposure to radiation would be very cost effective for extending the life of existing pressure vessels. Promising new techniques have been suggested by a program sponsored by the Nuclear Regulatory Commission. [3]. In the area of fatigue life prediction, acoustic harmonic generation has shown considerable promise, showing a much stronger correlation with remaining life than measurements based on linear effects such as ultrasonic velocity and attenuation.

An alternate futuristic approach to property determination is the monitoring of appropriately representative test coupons. For example, fatigue damage accumulation in reactor pressure vessel steels might be measured on test coupons by selected area diffraction, which can measure the change in the cell-to-cell angular misorientation within each grain as a function of damage evolution. More comprehensive studies are needed to develop and validate such techniques and to determine how their performance compares to that of the in-situ measurement techniques discussed above.

In the measurement of material properties, there are two distinct kinds of problems. As noted above, a measurement must be made that is related to the property of interest based on solid physical principles, and some promising candidates have been identified. However, more research needs to be done to gain the level of understanding of the measurement-property relationships needed to guide their implementation with high confidence. In addition, it is often the case that there are considerable geometrical challenges. An example is the fact that embrittlement needs to be sensed in pressure vessel steels that are covered by a stainless steel cladding. Research directed at overcoming these challenges is needed.

It is important that there be a strong coupling between research in NDE and materials science. Mechanisms of degradation must have been identified and understood before acceptable tests can be developed. For example, improved understanding of pitting mechanisms and SCC crack growth phenomena are needed to predict the life of steam generators to avoid enormous costs associated with downtime. It is also important to recognize that new materials and material modification approaches are constantly being developed to improve corrosion and radiation resistance, and it is important that appropriate NDE approaches be developed hand-in-hand with these materials efforts. For example, surface modification procedures are used to either increase resistance to corrosive environments or to enhance specific mechanical properties of materials. Such procedures utilize a variety of methods ranging from relatively simple electrochemical approaches to ion implantation and laser irradiation techniques. Electrochemical deposition methods are also being looked at for repairing leaks in steam generator tubes. New generation nuclear power plants would most likely use a large number of surface modified components, and the development of inspection techniques tailored to their unique problems will be needed. These developments may involve some particularly challenging physical problems, since the dimensional scales of a few microns are in the transition region between mesoscopic and macroscopic dynamics.

It has been noted previously that it is highly desirable that measurement output be given in a probabilistic format. This is important in order for the measurement results to be readily utilized in systems analysis procedures such as probabilistic risk assessment and strategies such as defense in depth.

In future reactor systems, there will be an increased opportunity for condition monitoring (the continuous monitoring of flaws and or material properties) [4]. An important research direction is the development of the appropriate sensors, based on solid physical principles, that can survive when continuously exposed to the reactor environment. The development of new smart materials with the ability to provide in-situ on-line monitoring of material characteristics such as remaining cyclic stress fatigue life, velocity of crack growth, or time to reach critical crack length would increase safety, reduce conservative factors of safety, and provide consequential increases in plant operating efficiency. Ideally, outages could be scheduled based on the true condition of materials rather than a preset time schedule. An attractive feature would be the development of wireless communication procedures to allow the information to be transmitted to a remote site.

Although not part of the reactor per se, the high-level waste processing and storage issue should not be neglected. Research addressing the questions of NDE monitoring of the processing procedures and assuring the integrity of the containment vessels is needed.

There are a large range of emerging research tools that should be explored in the context of the above problems. Broad areas that might provide a basis for major advancements in NDE and condition monitoring may include, but are not necessarily limited to, advanced physical acoustics, positron annihilation, high intensity X-rays, superconducting quantum interference devices (SQUIDs), and artificial intelligence.

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MATERIALS ISSUES IN ACCELERATOR TRANSMUTATION OF WASTE (ATW) TECHNOLOGY

In ATW technology, as in other complex nuclear systems, the resolution of crucial materials issues will determine the success of the technology. In this concept , the target/blanket assembly (also known as the transmuter module), serves as the target for a high power proton accelerator operating at GeV energy. See, for example, references [1] and [2]. In this module, a heavy metal such as a liquid lead-bismuth eutectic (LBE), or solid tungsten serves as the spallation neutron source, wherein several tens of neutrons are produced per impinging proton. Immersed in and surrounding this target are the fuel elements of a sub-critical assembly, which contains transuranium elements, such as the actinide plutonium, and rods containing long-lived fission products, both of which are produced in the cores of LWRs. The actinides are destroyed by fission reactions, while the fission products are rendered stable or transmuted to short-lived radioactive products by neutron absorption reactions. In these processes, heat is produced, which may be harnessed for the production of electricity.

Issues requiring advances in materials science and engineering are numerous in the design, fabrication and performance of the target/blanket module. Other important materials issues must be addressed in the separation and fabrication processes entailed in producing and disposing the actinide- and fission product-containing host forms. The issues for the target/module design, fabrication and performance are in some cases similar to those already addressed in the work already underway for the Spallation Neutron Source at Oak Ridge, and other high power spallation neutron sources in design in Europe and Japan. In these spallation neutron sources, the spallation neutrons are moderated and subsequently directed to neutron scattering instruments for materials research, rather than being absorbed for producing neutron transmutation reactions in a waste blanket, as in ATW technology.

Key issues in the target/blanket module revolve around radiation damage by the proton beam and by the neutrons generated in the heavy metal target, as well as compatibility with the liquid metal coolant, or with water in the case of a solid tungsten target. Satisfactory lifetimes of the components in the radiation, thermal and chemical environment must be ensured. Materials performance will determine the feasibility, reliability and economic cost of this technology. Target containment and structural materials will need to be identified and subjected to experimental radiation effects studies and compatibility testing. Analysis and modeling must be an important part of this work in order to make use of irradiation results from materials irradiated in spectra different from spallation spectra, such as the huge amount of data already available from research reactors, LWRs, and charged particle irradiation experiments. LBE loops will need to be fabricated to study compatibility issues in unirradiated materials. Ideally, in the research and development for ATW, specimens should be subjected to high energy proton fluxes while under stress and immersed in high velocity, high temperature LBE in order to better simulate the synergistic effects that will be encountered in the actual application.

Exposure of materials at spallation neutron sources to the incident protons and spallation neutrons can be shown to produce much more hydrogen, helium, and heavier transmutation species than is the case for exposure to fission neutrons. Most of the transmutation products are produced by the proton beam and by the high-energy tail of the neutron spectrum. Except for this high-energy tail, the spallation neutron spectrum is otherwise not drastically different from a fast fission neutron spectrum. This additional burden of radiation-produced impurities can be expected to exacerbate radiation damage. Calculations give production rates of helium and hydrogen up to about 100 appm He/dpa and 1000 appm H/dpa; by contrast, the ratio for fission reactor irradiations is less than 1 appm He/dpa and for fusion reactors it is about 10 appm/dpa for both H and He. Radiation induced swelling may be a significant issue for the contemplated temperatures of the target/blanket module. Hence swelling should be investigated in the temperature range and for the candidate structural materials anticipated for ATW design and operation. Irradiation creep is relatively temperature insensitive and, therefore, will occur at the temperature of operation of the ATW. Whether it is a significant life limiting issue will depend on the design of the target. An open structure will not pose as many problems as a close fitting array of rods with small gaps and fine tolerances, for example. The interactions of these dimensional instabilities, radiation induced swelling and creep, will need to be understood and the consequences assessed in R&D leading to the deployment of the ATW. There is a reasonably well developed background on these two phenomena in terms of both theory/modeling and fundamental experiments [3]. Radiation embrittlement is expected to be an issue that may be important and which must be dealt with by materials selection and design based on theory and modeling and new experimental knowledge.

Liquid metals can be aggressive media, and corrosion and compatibility studies must be included in the research and development program as mentioned above. Two issues should receive particular attention: liquid metal embrittlement and temperature gradient mass transfer. In the former, grain boundaries may be sites of increased penetration and crack initiation by the LBE, especially under stress. In the latter, generalized corrosion may occur, in which structural materials are preferentially dissolved at higher temperature regions and re-deposited at lower temperature regions of the module. In the extreme this process may lead to flow blockage or structural compromise of components. The effects of irradiation on these processes are presently unknown but may be significant in terms of synergistic degradation processes.

A surveillance program for ATW materials should be planned, in which target materials are located in or near the target and removed periodically for materials characterization and testing.

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MECHANICAL BEHAVIOR, PREDICTIVE MODELING AND COMPUTER SIMULATION

The loss of fracture toughness and ductility, along with the deleterious effects of creep, swelling, and stress relaxation are of critical importance to reactor safety, lifetime, and performance. No unified model covering all length scales can successfully explain either deformation or fracture. Dislocation theory has achieved some success on a microscopic length scale; continuum elasticity and constitutive equations that are based on it have achieved some success on a macroscopic length scale. What is lacking is a unified model that can effectively incorporate aspects of both dislocation theory and elastic-plastic continuum models at the critical interval between typically 0.1 micron and 10 microns, where these highly successful models do not converge. Note that this interval corresponds to the size regime of microstructural features that may be controlled by appropriate synthesis and processing parameters.

It is still not possible to formulate an accurate theory of work hardening or dislocation cell formation during deformation. Incorporation of alloying elements and secondary phases is handled by sophisticated empiricism and requires detailed mechanical property testing to develop appropriate constitutive relations suitable for finite element models.

There is a lack of understanding of the evolution of the defect state, microstructure and microchemistry associated with the cumulative damage caused by below-yield cyclic stress. However, a solid that is subjected to such cyclical stress has a "memory" for its cyclical stress history, implying that there is associated cumulative damage. The challenge is to identify and quantify this damage. Corollary challenges are to find an experimental diagnostic that can be used to characterize this damage, and to correlate this defect state with the remaining safe life before failure.

There is no first principles understanding of the concepts of fracture toughness (proportional to the energy required to propagate a stable crack) and the brittle-ductile transition. One challenge is to develop a predictive model for the calculation of fracture toughness for a given material a priori. A corollary challenge is to predict the temperature at which a material undergoes a transition from brittle to ductile fracture. The old problem of explaining such a striking variation over such a small interval in temperature in many body-centered-cubic structured metals and alloys, including ferritic steels, remains; it has never been traced to any observable changes in microstructure. Creep deformation leading to fracture is often estimated using empirical time-temperature parameters based on invalid assumptions. A first principles approach to identify and characterize the cumulative damage from applied stress and temperature is required.

There is now an unprecedented opportunity to exploit emerging computational and analytical tools for the study of fundamental issues in dislocation motion and interaction. These new tools include include massively parallel processing computer codes and machines, new techniques for establishing activation energies from atomistic calculations, and for simplifying computations involving distributed dislocations (mesoscopic scale), and in-situ X-ray techniques for direct, real-time dislocation studies (densities, types, and patterning). The anticipated advances in understanding would span the length and time scales of individual dislocation motion, the intersection of grain boundaries by dislocations, the formation of dislocation networks (the patterning problem), and the deformation of polycrystals (work hardening). We are now ready to start solving these fundamental materials science problems that are critical to developing unified, first principles models of deformation, fracture, and damage and thereby advance our understanding and control over mechanical behavior.

In addition to mechanical behavior, the ability to predict the effects of radiation, applied stress, elevated and cycling temperatures, and hostile chemical or corrosive environments over all dimensional scales is necessary to reliably forecast the performance of reactor components over long times (perhaps beyond 60 years, and certainly well beyond laboratory test durations.) Computer simulation is now nearly as powerful as experiment and theory. Simulations are used to interpret experiments, to investigate phenomena, to predict properties, and to test mathematical models. Multi-terascale computers will have a revolutionary impact on materials science in the mesoscale size range. Currently, terascale simulations using first principles quantum mechanics can model electronic structure to compute properties (bond angles, lattice parameters, thermal expansion coefficients) of ideal crystals and non-crystalline systems containing up to several hundred atoms. Other quantum mechanical methods, which sacrifice some accuracy and reliability by using parameters derived from fits to first-principles results or experiment, are able to simulate systems containing thousands of atoms. At the critical intermediate length scale discussed above, a trade-off between accuracy and model size has been necessary to simulate collective phenomena that transcend several thousand atoms. At the continuum level, simulations use experimentally derived constitutive and elasticity equations to model physical structures and macroscopic processes, typically using finite element methods.

However, predictive models at the continuum scale must be based upon more rigorous fundamentals, which requires multi-terascale computing. It is crucial to couple first principles electronic and atomistic calculations to mesoscale simulation, and then to finite-element continuum calculations, in order to simulate bulk materials properties accurately.

The ability to simulate those microstructural features that are essential to performance will make it possible to understand the relationship between synthesis, processing, structure and performance. As discussed above, many important properties of materials are determined not at the atomic scale, but by collective phenomena involving large numbers of interacting atoms. Furthermore, materials processing frequently controls features at the mesoscale, such as grain size, to optimize a desired property. Rigorous simulations of complex materials and their time-dependent behavior in the hostile environment of a reactor will lead to the development of new and improved materials, and thus enable safer, more environmentally benign, longer operating, better performing and economically superior reactors and radioactive waste containment systems.

RADIATION EFFECTS

Radiation effects result from the interactions of neutrons, fission fragments, electrons, ions and gamma rays with materials. Radiation-induced changes in the microstructure, defect-structure and microchemistry greatly influence the lifetime-limiting corrosion and mechanical behavior of nuclear-reactor and power-accelerator components. These effects include enhanced diffusion, phase transformations, restructuring (as in the rim effect), loss of mechanical integrity such as fracture toughness or ductility, accelerated corrosion, significant swelling, and decreased thermal conductivity. Historically, research into these changes, known as radiation effects research, has made major contributions to fundamental scientific advances in understanding, e.g., the impact of lattice defects on materials properties, atomistic modeling of solid-state systems (including the development of computer simulation and of more accurate interatomic potentials), and the development of sophisticated technological methodologies such as ion implantation and ion-assisted growth of thin films [1-4]. Unfortunately, the decreasing emphasis over the past several years in the United States and Europe on nuclear technology has created a situation where many laboratory and university programs in this field have either disappeared, or are in an advanced state of decline. As pointed out in the President's Committee of Advisors on Science and Technology [5], this decline must be reversed if the United States is to maintain a position of leadership in nuclear technologies and underlying scientific areas.

While much work has been done on radiation damage fundamentals in simple alloys, particularly on elemental metals in the 1960's and 1970's and on model binary alloys in the 1980's and 1990's, radiation effects in engineering steels and advanced ceramics or composites are not well understood. Perhaps this situation is best summarized by noting that in the current state of affairs for metals, where the accumulated knowledge is the greatest, it is still unknown whether the vacancy or the self-interstitial defects created in steels are more mobile. The lack of knowledge regarding radiation effects in insulators, advanced composites and ceramics is considerably worse. Hence we are far short of being able to formulate reliable predictive models of the effects noted in this report. A fundamental understanding of the mechanisms and kinetics of microstructural and microchemical evolution, and corresponding property changes, during irradiation is necessary.

The radiation-induced restructuring of nuclear fuels at high burnup and high temperatures also greatly affects their performance. To understand radiation-induced changes in macroscopic engineering properties, an atomistic understanding of radiation damage mechanisms is required. Furthermore, radiation effects occur over the lifetime of the plant (30 to 60 years, and possibly longer depending on license renewal) or storage time of nuclear waste packages (thousands of years). Fundamental radiation damage states and kinetics must be understood in order to make longer-term predictions based on data that are often obtained for shorter times and higher dose rates.

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HIGH BURNUP FUEL PERFORMANCE AND ADVANCED FUEL MATERIALS

National and international trends in nuclear fuel utilization are towards higher burnup, up to 75 GWD/MTU. There are indications of interest to eventually push the limits to even higher values. Increased burnup and longer reactor cycles have very attractive economic features. In addition, extended burnup can lead to fewer fuel assemblies that must be stored on site and ultimately disposed of in a national repository. However, higher burnup will also lead to higher activities and concentrations of transuranics, which may dictate fewer assemblies per waste package, or even alternative approaches to disposition, such as partitioning and transmutation. Furthermore, as the burnup of UO_2 fuel reaches higher levels, significant new phenomena or more extensive effects from known phenomena are being identified which must be understood and accommodated in the fuel designs, core management schemes, and operating strategies. These include fission gas release, restructuring of fuel (as in the development of the "rim" effect), pellet-clad interaction, and clad behavior.

Next-generation reactors for nuclear power may differ significantly from present designs, utilizing gas or liquid metal cooling that allow much higher operating temperatures and efficiencies. High burnup under higher operating temperatures may yield phenomena not yet observed.

Longevity of reactor fuels has a major influence on operating economics. Current fuel designs have been taken to their regulatory limits. To achieve significant increases in average core burnup requires the development of advanced fuels based on either traditional fuel materials (e.g. UO_2, or UO_2-ThO_2) or advanced fuel materials or concepts (e.g. metallic fuels, carbide fuels, pure actinide fuels, or composite fuels, including inert fuel matrices). Understanding the performance (changes in microstructure, defects, and defect distributions, and changes in mechanical, chemical, and nuclear properties) of these fuel types must progress to the stage where it can contribute to reliable predictive modeling and improved fuel lifetime. In such an endeavor, one must think beyond water-cooled systems. Fundamental understanding necessitates the capability to predict, test and verify performance under both steady-state and transient conditions. With advances in computer simulation and modeling capabilities, the performance of advanced fuel materials under operating and transient conditions will become predictable based on physical processes occurring from the atomic to macroscopic levels. This could eventually eliminate the need for long testing programs and empirical models. Significant gains will be realized by continued experimental and theoretical materials developments. Clearly, the impact of higher burnups or new fuel materials on proliferation, disposition costs, and public safety may be significant.

CLAD PERFORMANCE

Increasing demands are being placed on clad performance as fuel burnup targets are being extended. This is critical because the cladding is the first barrier to the release of radioactive fission products to the reactor coolant system and potentially beyond. In addition, envisioned burnup limits will require the development and qualification of new clad materials that meet higher performance criteria. Advanced reactor concepts that incorporate gas or liquid metal coolants, in addition to high burnup, will greatly challenge cladding performance. With rapid developments in the area of ceramic composites that do not exhibit brittle fracture, fiber-reinforced ceramic cladding may be feasible in the foreseeable future. It is critical to understand phenomena such as corrosion, mechanical properties, radiation effects, phase behavior, fretting, thermodynamic performance, and other aspects of existing and new clad materials under all conditions that may exist in future nuclear power systems. Rather than empirical performance models, scientifically based performance models will provide more reliable predictions of behavior over a much wider range of conditions, potentially at great cost and time savings. Great gains in performance and safety may be realized by materials and theoretical developments in this area.

HIGH-TEMPERATURE MATERIALS PERFORMANCE AND AGING

High-temperature materials clearly cross cut and impact many of the topics and issues discussed already in this report. The development and utilization of such materials will vary with specific application, but in all cases significant improvements in safety and reliability can be realized. Potential improvements comprise all aspects of high-temperature materials behavior including mechanical, chemical and physical properties, as well as the effects of radiation and thermal aging. Investigations are needed to explore the parameters of both existing and future operating conditions. The performance of new high-temperature alloys, ceramics and composites in reactor environments must be studied and understood well enough to permit reliable modeling of materials degradation and component lifetimes. With advances in understanding and computer modeling capabilities, scientifically based predictions of high-temperature materials behavior will become possible.

To fulfill the need for safer, more environmentally benign, longer operating (60 years and beyond), better performing, and economically superior nuclear power reactors and radioactive waste containment systems, reliable predictive models for the long-term behavior of reactor materials under the combined conditions of applied stress, residual stress, radiation, temperature, and corrosive environments are also required. Although aging, like high-temperature performance, again crosscuts many of the research needs that are described above, it too is identified here separately in order to emphasize its importance.

The significance of understanding aging phenomena is perhaps most self evident for nuclear waste forms. Considerable work has been done on radiation effects in nuclear waste forms as compared with natural materials (e.g., actinide-bearing minerals,[1,2] and the corrosion of nuclear waste glasses[3,4] .

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CONTRIBUTORS TO THIS REPORT

This report is derived from contributions at a workshop that was under the direction of the Department of Energy's Nuclear Energy Research Advisory Committee that took place on 18 - 20 October 1999 and by extensive written electronic communications that took place over the duration from December 1999 through January 2000.

Those that contributed to the workshop on 18 - 20 October 1999 were:

Todd Allen, Argonne National Laboratory
Jerry Etheridge, Idaho National Engineering and Environmental Laboratory
Madeline Feltus, U. S. Department of Energy
Bob Gottschall, U. S. Department of Energy
Marty Martinez, Jupiter Corporation
Lee Peddicord, Texas A&M University
Lynn Rehn, Argonne National Laboratory
Bill Shack, Argonne National Laboratory
Ed Simonen, Pacific Northwest National Laboratory
Jim Tulenko, University of Florida
Bill Weber, Pacific Northwest National Laboratory

Those that contributed to the extensive written electronic communications in December 1999 and January 2000 were:

John W. Elmer, Lawrence Livermore National Laboratory
Rodney C. Ewing, University of Michigan
David W. Gandy, Electric Power Research Institute
Robert J. Gottschall, U. S. Department of Energy
Louis K. Mansur, Oak Ridge National Laboratory
Michael B. McNeil, U. S. Nuclear Regulatory Commission
K. Lee Peddicord, Texas A&M University
Lynn E. Rehn, Argonne National Laboratory
William J. Shack, Argonne National Laboratory
Edward P. Simonen, Pacific Northwest National Laboratory
R. Bruce Thompson, Ames Laboratory
R. (Viz) Viswanathan, Electric Power Research Institute
William J. Weber, Pacific Northwest National Laboratory

This report was compiled and edited by:

Lynn E. Rehn, Argonne National Laboratory
William J. Weber, Pacific Northwest National Laboratory
Robert J. Gottschall, U. S. Department of Energy

Appendix D

Working Group Report on – Reactor Technology/Nuclear Power Plant Design

Nuclear Energy Research Advisory Committee
Subcommittee for Long Term Planning for Nuclear Energy Research

Summary Report

Reactor Technology and NPP DesignWorking Group
December 8-10, 1999 Workshop

Summary Report

Reactor Technology and NPP Design Working Group
December 8-10, 1999 Workshop

Working Group Members:

John Herczeg (Chair)	DOE-NE
Roger Anderson	Northern States Power
William Andrews	PNNL
C.K. Chou	DOE-RW, LLNL
George Davis	ABB-Combustion Engineering
Harold Feiveson	Princeton University
Michael Golay	MIT
Yassin Hassan	Texas A&M University
James Hassberger	LLNL
Angus Hendrick	Naval Reactors
John Ireland	LANL
Peter Karcz	DOE-MD
James Lake	INEEL
Gordon Michaels	ORNL
Carter "Buzz" Savage	JUPITER
Arkal Shenoy	General Atomics
Michael Todosow	BNL
Gary Vine	EPRI
David Wade	ANL

Overview

The Reactor Technology/Nuclear Power Plant (NPP) Design Working Group conducted round table discussions to generate inputs for DOE-NE to consider in the development of its long term research and development program for nuclear energy, science and technology, specifically with respect to advanced reactor technologies and new nuclear power plant designs. The Working Group bore in mind the remarks that were made on December 8 by W. Magwood (Director, DOE Office of Nuclear Energy, Science and Technology) regarding Generation IV reactors and G. Rueger (Chief Nuclear Officer, Pacific Gas & Electric) regarding long term R&D needs of the nuclear utility industry. This summary report presents the input from the Working Group, arranged in near-term and long-term research needs. In general, the group reached consensus on the input, although individual members did not always agree on the subtopics, priorities or timing for specific research into advanced reactor technologies.

The summary report attempts to provide this working group's answers to the list of questions listed in the workshop breakout session process and outcomes guidance document. The questions were:

- What DOE-NE nuclear energy mission and objectives does this working group's R&D topic area support?

- What should the long-term role of the Department of Energy be in conducting nuclear energy R&D in this topic area?

- What specific R&D (subtopics) should the Department's Nuclear Energy Program focus on over the next decade? Identify any significant drivers for this needed R&D.

- What nuclear energy R&D will be conducted in this broad topic area outside of any DOE involvement?

- What are the challenges or barriers hindering R&D in this topic?

In addition to these questions, the Working Group was asked by Dale Klein (NERAC Subcommittee on Nuclear Technology Roadmap) to identify facility and infrastructure needs to support the research areas the group listed. Little input was developed for this question due to lack of time.

In its process discussion, the Working Group developed a list of items to aid it in applying "outside the box" thinking to the development of research ideas. The list included understanding the customer and his/her needs, the infrastructure that would be required to support the research and its availability, taking the human factors perspective into account in any new advanced designs, the recognition that any new design must be cost competitive in whatever environment it may be installed, proliferation resistance, and the need for a multi-track program for near- and long-term research.

As a result of the last item mentioned above, a dual-track research strategy was recommended, having both a near-term (next 5-15 years) and long-term (15 years and longer) component. The near-term research would be evolutionary, focused on further improvements to existing Generation III designs to bring to market in the next 5-15 years. The long-term component would be revolutionary, and include new advanced Generation IV reactor(s) research, and look into new, untried uses for nuclear energy such as supporting a hydrogen economy.

The near-term research strategic focus areas include:

- Risk-informed design and regulation
- Advanced technologies for design, fabrication & construction, including seismic considerations.
- Advanced technology development to address proliferation resistance issues associated with existing and new designs. It was felt that today's U.S. LWR's with a once-through fuel cycle were proliferation resistant already.
- "Smart" Equipment. This includes self-diagnostics and self-monitoring.

The long-term strategic focus areas include:

- High Temperature Technologies. This includes research into the behavior and performance of materials, fuels, and coolant systems in high temperature environments. It also includes research into high temperature energy conversion systems.

- Energy Conversion (general). Different energy conversion systems should be evaluated, such as direct energy conversion. The uses of reactor heat also should be taken into account. There may be new arenas such as hydrogen generation in addition to the traditional uses of electricity generation, process heat, and desalination.
- Fuels. Long-term research into high performance, long lived, proliferation resistant fuels should be conducted. A separate working group is evaluating this topic.

Goal and Vision Statement

The Working Group struggled with a Goal Statement, as there was no consensus whether it should contain any quantifiable statements regarding economics, market share, high level waste reduction goals, etc. The agreed to Goal Statement is:

- To develop advanced reactor technologies that will allow highly safe new nuclear energy plants that are an economically competitive (Working Group #2 Economics provide metric) energy production alternative in the U.S. and around the world, while being responsive to environmental, waste management, and proliferation concerns.

Vision Statement:

- The U.S. Nuclear Energy R&D Program will create new nuclear options for worldwide nuclear power deployment that will improve the worldwide standard of living, global environmental quality, assure energy security and contribute to the security of nations.

Attributes/Drivers

Attributes of new reactor technologies and nuclear power plant designs are synonymous with the drivers of the research. That is, the end products of the research will be new systems that have the desired attributes. The technical issues that could hinder achieving the desired attributes will drive the research. The most important drivers are cost competitiveness, safety, and proliferation resistance. In the safety area, designs and the regulatory regime must be risk-informed.

The Working Group developed the following list of attributes/drivers for new reactor technology and nuclear power plant research:

- Low cost/cost competitiveness *
- Safety/risk informed design *
- Proliferation resistance *
- Increased plant efficiency
- Simplicity in design and operation
- Maintainability
- Research needs to evaluate the entire fuel cycle, not just the reactor
- New designs must be environmentally friendly
- Management of low and high level waste must be assured
- New systems, or at least some new systems, should be capable of multiple applications

* Most important

- New designs should be applicable anywhere in the world; i.e., we should focus on both U.S. and global market needs.
- New designs must have sustainable long term fuel supplies; they must serve as both short-term and long-term solutions to worldwide energy needs
- An infrastructure must be maintained that includes facilities and personnel needed to carry out a large research program , then build and operate new reactors
- Industry as well as government must commit to investing in long term R&D
- DOE should pursue near-term and long-term R&D programs in parallel
- The long-term component of the research program should initially pursue sustained research to address the key technical issues confronting Generation IV reactor concepts – specific technology (ies) selection will take place in a later phase of the program
- Any multi-track research program should be managed as an integrated program
- The research program should be based on long-term sustained federal funding, leveraged with international collaboration
- Research scope should include large scale experiments & testing leading to prototype and demonstration plants
- An independent oversight group should be established to integrate and assess this research, as well as all other research conducted by NE.

Barriers/challenges

There are several barriers and challenges to performing a long-term nuclear technology research program. The Working Group discussed the following:

- **Stable, multi-year funding.** All participants sponsoring the research must provide stable, multi-year funding in order to maintain a long-term research program. This would include DOE, industry and international collaborators.

- **Lack of consensus.** Because of the uncertainty of the future role of nuclear energy to meet the world's energy needs, a lack of consensus exists as to projected research needs and how to meet them. With the ongoing keen competition for research funds, a united approach to research from all sponsors will be necessary.

- **Facility availability.** Research facilities around the world are aging, and plans to replace or upgrade them to meet future research needs are difficult to predict. The Nuclear Technology Roadmap subcommittee of NERAC is assessing projected facility needs to conduct long-term nuclear R&D. The two subcommittees need to work closely in order to ensure that gaps in projected facility availability are identified and plans to close the gaps are included in the research plan.

- **Personnel**. Personnel availability to carry out a large research program, then build and operate new reactors will be a challenge. Issues include retirement of senior researchers and the declining ability to attract and retain young scientists and engineers in the nuclear technology fields.

- **Insufficient industry investment in long term R&D.** Industry is currently able to fund the short-term research that is needed to help maintain current plants operating safely and profitably. Industry is interested in helping identify long-term R&D needs, but has limited ability to fund long-term research at this time. This was emphasized in Greg Rueger's talk. To interest industry to commit to investment of funds for long-term research is a challenge to DOE. A shift in regulatory environment as well as economic incentives will be required.

Long Term Role of DOE

The group generally felt that DOE should take the lead for initiating and maintaining a long-term nuclear energy R&D program. It should leverage its investment with participation and funding from industry and international collaborators. The institutional issues of high level waste management and recycling of spent fuel must be addressed by DOE since they will impact decisions on advanced reactor technologies selection.

R&D Needs

The Working Group concluded that a dual track approach to the research program in reactor technology and nuclear power plant design is appropriate. Both near-term and long-term research, as defined above, should be pursued. The focus of each of the two efforts would be different.

The group generated a list of generic research areas to be pursued, many in both the short- and long-term research paths. A few were recognized as being especially important, but no further attempt was made to prioritize the generic research areas.

- High temperature materials *
- High temperature fuels *
- Energy conversion technologies *
- Risk-informed design and regulation *
- Fabrication and construction technologies *
- Controls/Information Technology
- Alternate applications (other than electric generation)
- High level waste burners
- Coolant technology
- Process heat
- Recycle technology
- Large capacity reactors
- Small capacity reactors

- Thermal and fast neutron spectra
- Thorium and other cycles
- Peaking plants
- Computational methods
- Chemical processes
- Reactivity Control
- Passive safety
- Human factors

  * High priority

The group felt that near-term research should be conducted in the following topic areas:

- Virtual construction, life-cycle information management, and fabrication/construction technologies *
- Risk-informed design & regulation *
- Smart equipment *
- Seismic design *
- Higher burnup fuel
- Reliability engineering
- Virtual reality testing
- Small reactors
- D&D technologies
- Analysis methodology for design & safety
- Fuel forms

  * High priority focus areas

The long-term component of the reactor technology/nuclear power plant design research program would initially focus on the development of high temperature materials, coolants and fuels, energy conversion technologies and fuels in general. Later on in the program, the emphasis would eventually shift to the development of one or more specific reactor designs. Large scale testing might occur before specific designs are selected, but prototypes and demonstration plants would not be built until designs have been selected and developed adequately. The group agreed that any new reactor concept that gets selected for development must be pursued through design certification by the Nuclear Regulatory Commission. This would apply to designs intended for export or domestic applications.

The long-term research program might lead to the development of one or more new designs of advanced water reactors, gas-cooled reactors, or metal-cooled reactors. In addition, several other concepts were discussed for possible development, including molten salt reactors, liquid fueled reactors, advanced high temperature reactor designs, gas-fueled reactors (e.g. ultra-high temperature), large capacity reactors (many gigawatts), and subcritical reactors. Specific research areas were identified and prioritized by the group for water, gas and metal cooled reactors and are listed below. This level of detail was not completed for the other concepts mentioned.

Long Term Research – Water Reactors

- Superheated and super-critical steam systems *
- Long life fuels/new fuels/fuel forms(R) *
- New core assembly configurations, including fast spectrum cores (R) *
- Heavy water systems? (This may be a non-starter because of proliferation concerns)
- New energy conversion systems (R) *
- Recycle technology
- Advanced steam generators (R) *
- Small reactors (100-300 MWe) (R&D) *
- Advanced claddings
- Advanced structural materials
- Severe accident mitigating systems
- Containment systems

* High Priority R – Research D - Development

Long Term Research – Gas-cooled Reactors

- Magnetic bearings (D) *
- Helium turbomachinery (D) *
- High voltage connectors
- Helium recuperators (R&D) *
- Pre- and inter-coolers
- Insulators (R)
- Non-metallic control rods (R)
- Demonstration of passive safety systems
- Carbide fuel recycle
- Ceramic fuels (R) *
- Systems analysis
- Chemical reformers
- Multi-unit digital controls

Long Term Research – Metal Cooled Reactors

- Materials compatibility with coolant (R) *
- Pb, Pb-Bi, Na, and Hg coolant technology
- Reactivity controls
- Basic nuclear data (R) *
- Corrosion control
- Fuels (R) *
- Direct contact heat exchangers
- Passive safety systems
- New energy conversion technologies (e.g., direct, gas) *
- Recycle schemes (R) *
- Critical experiments

Recommendations

The Working Group made the following recommendations regarding a long-term research program in reactor technology and nuclear power plant design:

- DOE should pursue a dual track, and conduct a near-term and long-term R&D program in parallel
- The program should initially pursue sustained research to address the key technical issues leading to Generation IV reactor concepts. A focus on high temperature behavior of materials, coolants and fuels, and energy conversion systems is suggested. Selection of specific Generation IV reactor designs to develop, test, demonstrate and build should be delayed to a later phase of the program.
- The program should be managed as an integrated program
- Any long-term research program should be based upon long term sustained federal funding, leveraged with international collaboration
- The scope of the research program should include large-scale experiments & testing, even in the early phases before selecting specific reactor designs to develop.
- DOE-NE should establish an independent Office of R&D Integration and Assessment. This office should conduct planning, analysis and independent external oversight of all NE research programs. It would provide direction to keep the research programs focused on energy security, projected customer needs, leverage industry and international participation, and eliminate redundant research among various internal and external organizations.

Appendix E

Working Group Report on – Nuclear Plant Economics

Nuclear Energy Research Advisory Committee

Subcommittee for Long Term Planning for Nuclear Energy Research

Summary Report
Nuclear Power Plant Economics Working Group
Dec 8-10, 1999 Workshop

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NPP Economics Working Group Charge and Scope

Charge: Provide input to a long-term R&D plan whose projects reach fruition in 2015-2020. This is when the ten-year U.S. design certifications for Generation III built overseas will first expire and need to be renewed, and when preparations may begin for demonstration of a Generation IV reactor in the U.S.

Scope: NPP Economics R&D includes advancements in methodologies and technologies associated with the design, fabrication, manufacturing and construction, and operations and maintenance of nuclear plants to reduce costs. We primarily focus on actions that the DOE can take over the next 20 years.

Objectives for Generations III and IV

A number of tough market objectives for Generation IV were suggested:

- A price goal of 3¢/kWhr (breakdown given below). This is the overall objective, with suggested cost and performance targets given below.
- Capital cost of $750/kW (overnight).
- Thermal efficiency greater than 50%.
- Construction time less than 24 months.

A number of achievable market objectives for Generation III were suggested:

- A price goal of 3.5¢/kWhr, down from 4.1¢/kWhr projected for the early units.
- Capital cost less than $1200/kW, down from $1500/kW for the early units.
- Efficiency of 36%, up from 33% for the early units
- Construction time of 30 months, down from 36 months for the early units.

Natural-gas-fired combined cycle competitive economics, which will have to be met, were suggested:

- A price of 2.5–3.3¢/kWhr.
- Capital cost of $580/kW.
- Efficiency of 55–60%.
- Construction time of 24 months.

For purposes of program planning, it is assumed that the fossil plant competition will not be hindered by cost internalization of their green house gas emissions or by a carbon tax and that fossil fuel supply and price will remain stable.

Set an aggressive schedule for the R&D program, although it goes against the prior experience (a proposed schedule is developed next).

Proposed Phasing of the Generation IV Program

Research 2000–2005

Investigation of multiple technologies. This will require much more funding than the Nuclear Energy Research Initiative (NERI) by one order of magnitude—$200M/yr—and maybe more time. The first phase is an expanded NERI in both magnitude and scope which should provide the basis to select the two most promising technologies for intensive development. Due to the federal budget cycle, it cannot start before FY 2002, and may need more than five years to the downselection of technologies for the next phase.

Development Phase I 2005–2010

Downselect to two technologies, based on projected risk-adjusted cost. Address regulatory issues.

Development Phase II 2010–2015

Testing of components and subsystems. Licensing of full design.

Demonstration 2015–2020

Construction of full-scale prototype. Financing by either the federal government or an industry/government partnership.

Deployment beginning in 2020

Drivers of NPP Economics

Economic Drivers are the Primary Issue for the Generations III and IV

- Capital Cost
- Efficiency
- Capicity Factor
- Construction Time
- O&M Cost
- Additional Applications

Proposed R&D Topics to Address Each Driver

1. ***Total capital*** [the numerator in $/kW]. Alternative: MW per unit volume of the plant.

Value	Urgency	R&D Topic/Subtopic	Generation
1	B	System optimization:	IV
		Optimization of module size and configuration, and major components	
		Volume and footprint minimization, system optimization through systems engineering and trade studies	
		Unique approaches to modularity (for example, modules built up with variable numbers of components fit within an overall envelope, allowing the system to have a selectable electric output, etc.)	
1	C	Repowering reactors (internals replacement/upgrade following end-of-life)	II
2	B	Containment liner technology (significant cost reduction is needed over steel lined concrete–e.g., with advanced coatings).	III, IV

Value: 1 = High (significant contributor to achieving goals), 2 = Medium, 3 = Low (but still worth undertaking)

Urgency: A = High (begin now), B = Moderate (can delay for a few years), C = Low (can delay until a later phase of the program)

2. *Efficiency* [determines the denominator in $/kW]. Alternative: Electrical output.

Value	Urgency	R&D Topic/Subtopic	Generation
1	A	Alternative cycles (possibly with alternate moderators):	IV
		Supercritical fluids	
		Direct cycle gas turbine (helium)	
		Liquid metal high temperature	
		Direct conversion of fission fragments to electricity	
1	A	Improved materials focused on high temperature performance	III & IV
2	A	Topping cycles (combustion superheating) to be added to nuclear steam cycles.	III & IV
2	A	Working fluid technology	
2	B	High efficiency turbines	III & IV
3	B	Bottoming cycles:	III & IV
		Desalination	
		Cogeneration	
3	B	Adjusted thermal margins (i.e., better understanding of margins through additional analysis)	II, III & IV
3	B	Power upgrade to current plants through improved instrumentation, and/or improved fuel design	II

Value: 1 = High (significant contributor to achieving goals), 2 = Medium, 3 = Low (but still worth undertaking)

Urgency: A = High (begin now), B = Moderate (can delay for a few years), C = Low (can delay until a later phase of the program)

3. Capacity factor

Value	Urgency	R&D Topic/Subtopic	Generation
1	A	High burnup fuel (analysis and testing)	II, III & IV
1	A	Advanced sensors	III & IV
1	A	Advanced surveillance and diagnostics	II, III & IV
1	A	Aging management	II, III & IV
1	B	On-line maintenance	II, III & IV
1	B	Improved major component reliability (steam generators are a major aspect of Generation IV liquid-metal-based concepts)	II, III & IV
1	C	Predictive maintenance and artificial intelligence	II, III & IV
2	A	Improved in-service inspection (ISI) for major (10 yr) outages	II, III & IV
2	C	On-line refueling (This was reduced in priority due to the potential for proliferation and licensing issues.)	II, III & IV
3	C	Outage optimization	II, III & IV
3	C	Supply chain management (Just-in-Time practices, etc.)	II, III & IV

Value: 1 = High (significant contributor to achieving goals), 2 = Medium, 3 = Low (but still worth undertaking)

Urgency: A = High (begin now), B = Moderate (can delay for a few years), C = Low (can delay until a later phase of the program)

4. Construction time

Value	Urgency	R&D Topic/Subtopic	Generation
1	A	Virtual reality for design, construction, etc.	III, IV
1	A	Procurement process control and automation	III, IV
1	A	Computerized process management	III, IV
1	B	Modularization:	III, IV
		Erection technology (e.g., use of multiple cranes)	III, IV
		Field assembly of modules	III, IV
1	B	Welding technology	III, IV
1	B	Reduce plant commodities (such as concrete), and/or use alternative materials.	III, IV
1	C	Factory fabrication, assembly, manufacturing and certification	III, IV
2	B	Analysis and optimization of structural margins, and/or use of alternative methods, e.g., replace the widespread use of rebar.	III, IV
3	C	Complete plant fabrication (barge or submarine-based mobile power plant)	III, IV

Value: 1 = High (significant contributor to achieving goals), 2 = Medium, 3 = Low (but still worth undertaking)

Urgency: A = High (begin now), B = Moderate (can delay for a few years), C = Low (can delay until a later phase of the program)

5. Operations and Maintenance Costs

Note: Personnel, outages and equipment are the big costs here.

Value	Urgency	R&D Topic/Subtopic	Generation
1	A	Design for reduced maintenance	III & IV
1	A	Waste management technology (e.g., dry storage of spent fuel)	III & IV
1	A	Improved I&C hardware and software	III, IV
1	B	Risk-informed regulation	II, III & IV
1	C	Staff size optimization	III, IV
1	C	Predictive maintenance	II, III & IV
2	A	Improved decontamination technologies	II, III & IV
2	B	Improve ISI technology and regulation	II, III & IV
3	A	Coolant chemistry control	II, III
3	B	Decommissioning	II, III & IV
3	C	Outage planning	II, III & IV
3	C	Supply chain management (e-commerce, JIT, etc.)	II, III & IV
3	C	Standardization	III & IV

Value: 1 = High (significant contributor to achieving goals), 2 = Medium, 3 = Low (but still worth undertaking)

Urgency: A = High (begin now), B = Moderate (can delay for a few years), C = Low (can delay until a later phase of the program)

6. Additional Plant Application and Byproduct Revenues

Value	Urgency	R&D Topic/Subtopic	Generation
3	B	Hydrogen production from process heat	
3	B	Materials production for space (Pu-238) or defense needs	
3	B	Process heat	
3	B	Medical and industrial isotope production	

Value: 1 = High (significant contributor to achieving goals), 2 = Medium, 3 = Low (but still worth undertaking)

Urgency: A = High (begin now), B = Moderate (can delay for a few years), C = Low (can delay until a later phase of the program)

Also mentioned in this category, but not rating any priority, were:

- Process steam
- Hydrogen via electrolysis (presumably in off-peak hours). This was not viewed as being distinct from any other electric generation capability being coupled with hydrogen production.
- Energy storage / nuclear-based renewables
- District heating
- Desalination

These were not rated because nuclear power does not provide a unique capability different from alternative electric generators. These applications none the less would enhance the overall benefit of nuclear power through its contributions to a broader energy sector than electricity.

7. Applicable Generic R&D Topic Areas

Of significant value is the application of on-going generic R&D, both within and outside the nuclear community, to the Generations III and IV development. The following chart summarizes these generic R&D topic areas and suggests their priorities in terms of the potential contribution to the economic drivers of Generations III and IV.

	Economic Drivers and R&D Topic Areas					
	Total Capital	Plant Efficiency	Capacity Factor	Construction Time	O&M Costs	Other Applications & Byproducts
Objective:	$750/kW*	> 50%	> 90%	2 years	3¢/kWhr**	
Overall Value	1	1	2	2	3	3
Research Priorities:						
Advanced Simulation	A	B	B	A	C	C
Construction Processes	A	C	C	A	C	C
Coolant Technology	B	A	B	C	C	C
Digital Technology	A	B	B	A	A	C
Human Factors	B	C	A	C	B	C
Information Technology	B	B	B	A	A	C
Low-Level Rad Health Effects	C	C	B	C	B	C
Materials	B	A	B	C	C	B
Mfg/Const Technology	A	C	C	A	B	C
Non-proliferation Technology	B	C	C	C	C	C
Nuclear Fuels	B	A	B	C	C	C
Operator Training	C	C	B	C	B	C
Reactor Analysis	C	B	B	C	C	C
Regulatory Reform	B	C	B	A	B	C
Robotic Technology	C	C	B	B	B	C
Safety Technology	B	C	C	C	B	C
Sensor Technology	B	A	A	C	B	C

Overview of the Relationship between R&D for Reactor Generations

Generation I

D&D is the central R&D issue today. Lessons learned are valuable for future generations and 'flow into' (i.e., benefit) them.

Generation II

O&M costs, safety and aging mitigation (capital additions) are the central R&D issues. Again, lessons learned and technologies will flow into future generation. Regulatory research is active, too, with risk-informed approaches that will improve the economics.

Generation III

Construction economics and O&M costs are the central R&D issues. Improvements are also flowing from the regulatory improvements ongoing. The forefront is modular design, virtual construction, and advanced project management. Starting in 1985, the first Generation III plant was designed and certified by NRC in 1996–a total of 11 years was required to do an evolutionary cycle. Based on that design and the NRC licensing reviews preliminary to certification, the plant was constructed in four years in Japan. Breeders as an example, spent 20 years in development and never completed a demonstration in the U.S., although a breeder demonstration plant and large-scale prototype were built and operated in France.

Generation IV

The central issue is, "What technology is most compatible with a global market economy?" The expectation is that with a substantial technology step from Generation III to IV, we will have some process improvements that flow from III to IV, but not all such improvements will be relevant. New areas will be needed, such as modular construction for nuclear plants being demonstrated in the U.S. Generation IV will hinge on (1) capital cost reduction and (2) the reduction of investment risk from waste management, safety, and non-proliferation issues.

Discussion

The first three generations were based on a technology that came primarily from submarine propulsion (i.e., LWR) technology. Generation IV may very well not be a light-water-based technology. Also, Generation II will still be needing license extension approvals at the time Generation IV is reaching definition. The R&D program will need to contain aspects of generations II, III, and IV, although much more heavily weighted to the latter than the former.

Generation IV has the opportunity to be based on a new, fresh approach. R&D can be structured logically with criteria, and with adequate technology choices. The model for the development of the program for Generation III was similarly structured, and could be used.

Comments on Related R&D being done elsewhere

Two countries are working on supercritical fluid thermal cycles.
One vendor is reportedly working on a steam turbine for NPPs with 4% higher efficiency.

Conclusions and Recommendations for the Presentation

Slide 1: Title page.
Slides 2 & 3: Cost is the fundamental barrier, and all objectives must support cost competitiveness. Objectives were formulated for Generation IV versus cost drivers.
Slide 4: Assumption–No easement of the challenge will take place through leveling of the playing field (i.e., carbon tax), although this may eventually come through slow, regulatory pressure.
Slide 5: Schedule should be aggressive. A schedule with phases was formulated.
Slide 6: The historical and future trend will be that research on early generations will almost always flow down to benefit later generations.
Slides 7–12 R&D topic areas were organized with respect to the drivers. Priorities and target generations were detailed. Other breakout sessions may have developed areas or groups of our topic areas in more detail.
Slide 13: General topic areas shown as a matrix that we intend to fill in.
Slide 14: Conclusions:

- Cost is the major barrier. DOE needs to embark on an ambitious R&D program to surmount the barrier, setting goals and striving to achieve them on an aggressive schedule.
- We have considered a general set of R&D areas. Priorities allow the selection of R&D areas to fit within the budget. Budget must be an order of magnitude above NERI, starting in FY 2002. This R&D program must be virile.
- An objective means of projecting the costs of various concepts is vital to the evaluation of the R&D projects.
- Downselection of Generation IV technology should happen about 3–5 years after a well-rounded set of technology concepts are seriously undertaken.
- The R&D program, and many policies of the U.S. government, will be greatly supported by international collaboration. The U.S. must be a serious "player" in Generation *R&D* to expect meaningful international collaboration.

Initial Comments

At the outset, each participant had an opportunity to comment on the process and/or the topic area. The comments were as follows:

- NPP competitiveness needs to get away from only being viewed in terms of economies of scale, and more into understanding the larger factors and interactions in the market framework.
- NPP is undergoing globalization. We need to understand how the U.S. fits into the world market framework.
- We need to think 'out of the box' in terms of what the power producer wants to buy, and then go after major improvements to halve the cost.
- Our group is very different from the others, we need to take into account the market factors that will set the targets that the R&D is to meet. We need to elaborate on the ground rules for reactors in that time frame.
- We must not just focus on Generation IV, because Generation III must succeed prior to the period 20 years out.
- We should depart from traditional 30 yr levelized busbar cost analysis–look at the desire for capital investment in terms of what would need to be considered to reach a decision by an executive today.
- We must stay focused on the domestic market, where Generation III is not competitive with combined cycle natural gas plants.
- The most important (Pareto analysis) factor is the plant capital: The current Generation III cost breakdown is 4.1¢/kWhr = 2.7 capital (based upon11% finance pre-tax real rate of return)+0.5 fuel + 0.8 O&M + 0.1 waste disposal + D&D. This is a 30 yr levelized cost analysis breakdown.
- One must look at the full 'going forward' costs, including general an administrative (G&A), capital additions, O&M and fuel costs–also referred to as production costs. This is about 3.5¢/kWhr. Also, the locational marginal prices need to be considered by completing a regional analysis. Each new plant must justify itself on its own expected revenues on a project basis, case by case. Locational market prices vary with the season of the year, with available local generation, existing demand and transmission capacity.
- Capital costs are tough to reduce, due to fundamental needs for radiation shielding, etc. The most important gain to be made is on reducing the lead time for construction. Also, there will be beneficial effects from R&D on project organization and finance.
- The playing field needs to be leveled with other energy sources, specifically with a full accounting of effects on the environment.
- Systems with hydrogen generation features may hold some benefit and should be studied.
- Prediction of the market 20 years out is difficult, if not impossible. Also, our long-term view may not be able to account for very new and diverse technologies (the impact of nanotechnology, e.g.) that will bring large improvements.
- There may be paradigms that can be broken in the nuclear industry, such as how one must build and test before deployment . The Boeing 777 aircraft was flown without testing, for example.
- The politics and cost of public acceptance need to be addressed in the economics.
- Economics must address the big uncertainties, which ultimately get translated into conservative assumptions. Also important are achieving very high reliability and standardization.
- Good advantages will come from design simplification, fewer parts, smaller components, reduction of machining of weldments, advanced methods of placement and insulation of rebar, and similar factors.

- Economics of all fuels must be analyzed with all of their real costs (even nuclear).
- Assuming nuclear is competitive in the future on a cost basis, there is still the consideration of the capital investment being at risk for a longer time until the plant becomes operational.
- The path to Generation IV is probably found going through Generation III plant introductions in Asia. That is, they will be linked.
- Observe that O&M costs were 'solved', i.e., greatly reduced by the industry, not by the plant design.
- Forecasts and models are very dismal on the environmental impacts of greenhouse gases, thus, the force for change to a preference for nuclear is already in action now.
- The challenge is to compete with gas-fired combined cycle plants having a capital cost in the range of $500/kW, which is equivalent to about a1¢/kWhr advantage. O&M adds 0.3¢/kWhr. Fuel costs of 1.7–2.0¢/kWhr are typical of the gas-fired competition. So current projections on natural gas prices yield a total generation cost of about 2.5–3.3¢/kWhr. No G&A or capital addition costs apply to these plants. This also assumes 6,000–6,600 BTU/kWhr heat rate (i.e. 55-60% thermal efficiency). There was some question of whether the turbine technology to achieve this efficiency was adequate. There was general consensus that the target competitive cost for Generation IV should be set at 3¢/kWhr. This is 1¢/kWhr lower than optimistic nuclear generation costs for plants that are being built now.
- The gap in nuclear/fossil plant economics would require a carbon tax of about $100/ton (for each 1¢/kWhr difference in generating costs) to bring nuclear (Generation III) into the same cost as combined cycle natural gas. There was some question about the elasticity of demand with these large proposed pricing changes. The conclusion is that carbon taxes are not likely to achieve a closing of the gap.
- Generation III could conceivably consider 'way-out' thermal efficiency improvement from supercritical steam cycles, for example, as a way of reducing the capital cost per kWhr.

Ideas and Debate

- A good potential idea is centrally-manufactured plants that are transported to the generation site (reactors using submarine reactor technology, for example). An ‘oldie but goodie’. Some doubt was raised about the economic viability of this idea. There are also a number of new problems involved with this idea in that the required high enrichments (HEU is typically required) will cause trouble with regulatory acceptance and proliferation resistance.
- Bring new innovations in technology to the nuclear business. Assembly and construction advances, for example. Procurement processes and inventory controls should be advanced, too. There was some question about whether this was really a long-term need, or whether the technology in these topics would be more likely improved in the near term.
- Study opportunities to bring major advances in other field to bear on the R&D program for Generation IV. Suggested subjects were nanotechnology, advanced simulation, advanced sensors and safeguards technology.
- Study graded quality assurance of equipment, a current issue with NRC but one that DOE should devote resources to. A number of similar ideas have been deemed acceptable to NERI, for example. These include virtual construction, satellite communications uplink of project information to and from the job site, etc. Other R&D topics are found in the areas of construction simulation, etc.
- Supply chain management should be studied.
- DOE should establish a center of excellence to highlight and encourage more of the process-related R&D. Perhaps SNL would be a good focal point, due to its involvement in several projects of this type.
- Capital cost reductions–is modularization likely to achieve the goal? For example, 100 MW modules can be delivered to a site on a flatbed truck with attendant savings. Small modules may also fit better with the generation demand of developing economies. However, a factor of 10 reduction in size may equate to a factor of 3 increase in the loss of economy of scale. In response to this it was noted that the cost of equipment is not very affected by the module size, in fact. The big savings in modularization is actually found in the reduction of the time of construction.
- Study the optimal size module. Small modules hold a promise, but the target size needs to be optimized. Factor in the value of (and constraints inherent in using up) existing nuclear sites, too. An existing nuclear site is valued at about $100/kW. However, a number of small modules may require a larger footprint than large modules, and small modules may require more sites, ‘disturbing’ more of the population–this has been a problem in Japan.
- Develop ways to evaluate the projected economics of very diverse concepts that will be proposed for Generation IV in a fair and objective manner. Bring this to bear on the selection of NERI projects that are aimed at Generation IV. A good costing system should be available (at an independent laboratory or other entity).

- ANS ‘Economic Imperative’ exercise: Compete with the best current options, with no sudden fixes like carbon credits. The MIT project is in the lead, which is a He-cooled, pebble bed 100 MW reactor. It is based on an assumption of 50% thermal efficiency. They claim it can be built for $1000/kW. Credibility? The plant has no containment (other than the outer fuel layer—this will be hard to sell in the U.S. It is hard to imagine the whole plant costing only $100M. South Africa has reportedly spent $16M on this concept, after Germany got out. This is the most credible idea of the exercise, however.
- Berkeley has a Pb/Bi cooled reactor concept.
- Proliferation resistance may significantly weaken the NPP economics.
- International collaboration: Manufacturing has to go global.
- Anticipate the bureaucratic processes: DOE should begin working regulatory approval of Generation IV, similar to what was done with Generation III.
- NERI is not funded sufficiently to bring any project to a defensible conclusion in five years.
- We should develop the economic attributes expected of Generation IV.
- Typically the plant is built with sufficient margin for 110% output, which can often be exploited later.

Clarifications / Questions and Answers

- Should we consider overseas economics, or just U.S.?   A: No, we are free to consider both.
- What’s the purpose of this R&D that we recommend?   To facilitate a new U.S. reactor construction, for example?   A: This would provide a considerable focus. We should recommend objectives.
- Where should we draw the line on using sparse DOE funds to advance process R&D that is of great benefit to others involved with major construction projects?   A: It’s important to leverage with other industries.
- Are we too focused on LWR technology? (not answered)
- Can we look and advise beyond 2020?   A: Yes.
- What is the incentive of Generation IV?   A: It is the logical follow-on to a Generation II or III plant. It may also produce more than just electricity (e.g., hydrogen, process heat, high fuel conversion…).

Participants in the Nuclear Power Plant Economics Working Group

Alvin	Ankrum	PNNL	alvin.ankrum@pnl.gov
Ralph	Bennett	INEEL	rcb@inel.gov
Jake	Blanchard	U Wis. Madison	blanchard@engr.wisc.edu
Tom	Blejwas	SNL	teblejw@sandia.gov
Chaim	Braun	Altos Mgmt.	chbraun@earthlink.net
Harold	Dodds	U Tenn. Knoxville	hdj@utk.edu
Stan	Hatcher	Hatcher & Assoc.	shatcher@idirect.com
Dean	Pedersen	ANL	pedersen@anl.gov
Geoff	Rothwell	Stanford Univ.	rothwell@leland.stanford.edu
William	Sailor	Stanford Univ.	sailor@leland.stanford.edu
Phillipe	Savelli	OECD NEA	savelli@oecd.org
Robert	Schock	LLNL	schock1@llnl.gov
Ronald	Simard, Jr.	NEI	rls@nei.org
John	Taylor	EPRI	jjtaylor@epri.com
Richard	Turk	ABB CE	richard.s.turk@us.abb.com
Robert	Vijuk	Westinghouse	vijukrm2@westinghouse.com

Appendix F

Working Group Report on – Reactor Safety, Component Reliability/Performance Improvement and Aging

Nuclear Energy Research Advisory Committee

Subcommittee for Long Term Planning for Nuclear Energy Research

Summary Report
Reactor Safety, Component Reliability, and Aging Working Group
Dec 8-10, 1999 Workshop

SUMMARY REPORT

DOE Long-term Nuclear Energy R&D Plan Working Group on
Reactor Safety, Component Reliability, and Aging

Dr. Joseph Comfort, Arizona State University, Workshop Leader

Working group participants:

Todd Allen, Argonne National Laboratory
Deborah Bennett, Los Alamos National Laboratory
W. Gary Gates, Omaha Public Power District
Dave Hill, Argonne National Laboratory
John J. Hutchinson, ComEd Nuclear Generation Group
Natraj Iyer, Savannah River Technology Group
Barclay G. Jones, University of Illinois at Urbana, Champaign
Jim Lang, Electric Power Research Institute
Alan Levin, U. S. Nuclear Regulatory Commission
David Moses, Oak Ridge National Laboratory
Upendra Rohatgi, Brookhaven National Laboratory
Theo Theofanous, University of California, Santa Barbara
Robert S. Walker, Baltimore Gas & Electric

This report summarizes the discussions and recommendations of the Working Group #3 on Reactor Safety, Reliability, and Aging at the DOE Long-Range Nuclear R&D Workshop held in Washington, D.C., December 8-10, 1999.

Initial Question

As the working group got underway, a very important question was raised. How can the Working Group form a list of R&D topics when:

- The methods for dealing with the issues of safety, reliability, and aging depend on the specific reactor design, materials to be used, etc., and
- No specific long-term design or goal has been stated or identified.

It was noted, for example, that issues of corrosion would depend on whether the reactor was of a light-water design, a liquid-metal design, or something else, and on the interactions of the coolants with the materials utilized for the core and container. Once the design goal had been specified, the R&D could be tailored to provide the optimal cost and performance features.

Approach Taken

In resolving the question, it was agreed that the Working Group would focus primarily on enabling methods and enabling technologies. Research that was directed to important areas of fundamental science and engineering would provide a common base of knowledge for application to current and any future reactor designs. A number of shorter-term topics were also identified, primarily related to the information base which underlies the regulatory environment.

The Group did not attempt to identify topics individually for the issues of safety, reliability, and aging. It was recognized that these issues were not entirely distinct and that the enabling methods and technologies would have broad applicability. Participants associated with commercial power plants identified a number of items where the lack of fundamental knowledge necessarily led to conservative operating standards which limited plant efficiencies and enhanced costs. An enhanced scientific knowledge base would reduce the uncertainties associated with many of the items.

Implications for Reactor Design

The issues of safety and reliability are critical to the design of future reactors. The designs must also be thermodynamically competitive and cost effective. Thus, the use of materials which can withstand
higher temperatures (in a harsh radiation and chemical environment), and/or which can operate in environments other than water and steam will likely be very important to consider. These materials must also be highly reliable, and their reliability must be understood and well documented. A large amount of operational data related to component and system performance already exists, and these data will need to be extended, reviewed, and consolidated into reactor designs. Advanced monitoring techniques which enable timely operator intervention, along with passively-safe system and component designs will also be important for future designs.

Common Themes

Several themes came up repeatedly throughout the discussion of specific R&D topic areas.

* Critical Issues for Fundamental or Basic Science and Engineering Research:

> Common to many of the long-term topics was the importance of developing fundamental knowledge, reliable models and computational codes, and a much improved data base for testing and validating the models and codes. An incomplete understanding of the fundamental physical processes underlying the behavior or degradation of materials in the radiation and chemical operating environments of nuclear reactors and other key system components necessitates the imposition of large safety margins. With the development of new knowledge and detailed models, many uncertainties in the operations of current reactors or in the design of future reactors could be substantially reduced. The research would primarily be long-term, with intermediate-term benefits.

* Regulatory Issues:

> Due to uncertainties in our knowledge and the conservative nature of safety and reliability standards, it is believed that significant amounts of energy in the reactors are not being utilized. The potential for cost savings in current reactors or reduced costs for future reactors is quite large. It was frequently noted that ways need to be found for DOE and the NRC to work together in developing research-based data and information on licensing issues, without compromising the independence of the NRC. Such research is needed in order for DOE to obtain license approval for specific missions of the

Department, and to help make the regulations amenable to future designs and innovations.

* Multidisciplinary Aspects:

For many, if not all of these research areas, the work is broadly multidisciplinary in nature. To do such research in an effective and efficient manner, it is imperative that researchers in the various disciplines communicate and interact with one another. Effective coordination at the management level (top-down) as well as development and maintenance of a "teamwork" approach (bottom-up) is necessary. The historical pattern is poor. This concept applies both domestically and internationally, and with respect to communication with other relevant industries.

New technologies and techniques are being developed outside the nuclear power industry, and ways need to be found to adapt them to current and future nuclear facilities. While the regulatory environment currently limits some of the potential applications, it is also true that the poor state of nuclear R&D does not provide the people who could facilitate such adaptations. In particular, linkages between NE and other offices and programs in DOE, such as DP, NR, and SC, need to be established.

<u>Common Drivers</u>

The importance or need for many of the R&D topics were often driven by common concerns.

* Economics, enhanced efficiency, and life extension of facilities.

* The importance of safety, reliability, and aging were themselves driving issues.

* Reliance of old technologies:

Current nuclear power facilities are largely based on 1970's technologies. (Note that the personal computer age began in the 1980's.) Such technologies limit performance and need to be updated.

<u>Common Barriers</u>

A number of barriers or impediments which could inhibit development in the R&D topics were commonly identified.

* Regulations and uncertainty about changes:

The nuclear industry is tightly regulated. Changes in the operation of power plants require substantial technical justification and support. Uncertainties as to the willingness or ability of the NRC to modify the regulations sometimes inhibits an investment decision to undertake the necessary long- and short-term research.

* Database Inadequacies:

The development of computational models can be impeded by an inadequate data base for testing and validating the model. Furthermore, the original data from older research programs have either been lost or become irretrievably degraded, and even more-recently acquired data is in danger of being lost, because the resources and means for preserving and reading them are disappearing. Also, little work is being done on reviewing them and ensuring that their integrity is maintained. Similarly, the experience gained, in the form of "corporate memory," is being lost as older experts retire without being replaced or without transferring their knowledge to those who replace them.

* Complexity of the Problem

In some cases, the problem can be seen as sufficiency complex as to limit the ability to make fruitful developments within the appropriate time frame.

General Recommendations

The Working Group adopted two general recommendations with regards to future R&D in the topic area. These recommendations will be followed by a more detailed list of the specific topics.

1) DOE should support R&D in two broad categories:
   - Fundamental long-term science and engineering on enabling methods and technologies related to the safety, reliability, and aging of current and future reactor designs; and
   - Intermediate-term R&D related to diagnostic and monitoring methods and to regulatory support.
2) Wherever possible, DOE should ensure that the research be done with multidisciplinary coordination among all relevant DOE offices and other agencies to take advantage of the research being done there.

SPECIFIC TOPICS

Fundamental Research

A number of important research areas requiring D.O.E. support can be classified as "Fundamental Research." Advances in knowledge in these areas could lead to revolutionary advances in reactor safety, performance, and reliability. Therefore, support for research in these areas is critical. At the same time, progress in these areas requires advances in fundamental understanding and cannot be justified by the present-day nuclear power business climate. Because of the investment uncertainties, only the Government is likely to fund these far reaching research areas. The payoff in performing research in these areas is fundamentally long-term, but will provide some intermediate term benefit. The areas identified by the working group are:

* Environmental Effects on Materials:
Radiation effects, radiochemistry, corrosion, and technology for joining, including both experiment and advanced computational techniques. The radiation inherent in reactor operation creates a unique environment that can accelerate the degradation of certain reactor structural materials. Radiation effects such as loss of ductility, dimensional changes, and accelerated corrosion and cracking occur to some extent in any reactor design. Inadequate control of water chemistry can exacerbate these degradation mechanisms, as well. To ensure successful life extension in current water-cooled reactors and to improve the efficiency and economics of current and future reactor designs, a better fundamental understanding of radiation effects, radiochemistry, and corrosion in a reactor environment would be beneficial. Advances in the understanding of radiation effects would lead to improvements in plant reliability and component reliability and predictability.

To provide materials with improved performance in a reactor environment, the development of both advanced multi-scale computational techniques and experimental programs are required. Multi-scale modeling describes the combination of very-short-time/small-dimension- scale simulations with long-time/large-dimension simulations. Successful simulations combine basic radiation-damage simulations with microstructural evolution simulations to predict macroscopic behavior such as mechanical properties or corrosion. Experimental programs are required to understand degradation mechanisms and to support and validate computational techniques. Sufficient radiation testing and analysis facilities are required to support experimental activities. Future plants need to be designed specifically to include a materials surveillance program. Joining technologies and the effects of radiation on joined components form a special category within environmental effects.

To test a material's response to radiation, it must be irradiated. Accelerating the rate of irradiation can provide the correct fluence, but accelerated tests add an uncertainty in that the damage rate does not match that of actual reactor material. This limits the speed at which data can be acquired at actual reactor conditions. Therefore, research must be very forward-looking. Even for material behavior or fuel performance information needed in 10-20 years on, the experimental planning needs to begin now, so that sufficient time is available to irradiate the test materials/fuels to establish an adequate database for design evaluation and regulatory assessment.

* Fluid Mechanics:
Computational and multiphase fluid dynamics, fluid/structure interactions.

The ability to accurately model the fluid flow and heat transfer capability of reactor coolants is vital to understanding the margins to safety in any reactor plant. Continued improvement in design-basis accident (DBA) analytical tools have already, in some cases, resulted in elimination of these events from establishing limiting conditions for normal operation (e.g., peak fuel rod power, power shape, etc.) in currently-operating water reactors. This trend is expected to continue as more utilities turn to so-called "best-estimate LOCA" codes. As a result, transient events and local thermal-hydraulic (T/H) conditions will likely establish limiting operating conditions. This is expected to be true for future water reactor designs, as well. For other reactor types (liquid-metal or gas-cooled reactors), local T/H models are essential for analyzing core T/H performance. Improvements in smaller-scale, local thermohydraulics models (e.g., subchannel T/H models, computational fluid dynamics models) could lead to reduced conservatism and to improved economics in plant operations.

Computational and multiphase fluid dynamics techniques that accurately model fluid flow and heat transfer on all time and space scales are needed. Research is needed to improve both multiphase and single-phase fluid dynamics models. These techniques would range from small-scale simulations of localized effects such as boiling to large-scale full plant simulations.
The simulations also need to correctly model the coupling of the different scales in normal, transient, and accident conditions. Experimental work to support and validate computational techniques is also required. An example would be obtaining heat transfer data on supercritical liquids for advanced high temperature reactor designs. Additionally, experimental programs to provide improved knowledge of fluid/structure interactions will lead to improvements in plant reliability and component reliability and predictability. In addition to improved analytical techniques,methods that improve the ability of regulatory bodies to respond to new technologies would quicken the acceptance of these new technologies.

* Fracture Mechanics and Fatigue:
Experiment and multi-scale modeling.

Improved mechanical reliability and performance is critical to increased component lifetime, leading to improved economic performance. To increase service life, reactor components need adequate strength and ductility and the ability to withstand fracture. To meet this goal an improved understanding of crack propagation in an irradiation environment is required. The study of fracture mechanics, both experimental and multi-scale modeling is necessary to better understand and predict component performance. Another important area for fracture mechanics research is to find methods to incorporate probabilistic predictions into codes, so that the NRC can use them as it makes the transition to risk-informed regulation.

Thermal striping (rapid-thermal-cycle-induced fatigue) of plant components has recently caused cracking and failure of piping in operating plants in Japan and France . One of the fundamental limitations in understanding thermal striping is calculating the rapidly changing fluid temperature at the material surface. Limitations of both the single-phase computational fluid dynamics turbulence models in handling simultaneous momentum transport and energy transport and of the ability to calculate the behavior of the structure being thermally striped prevent understanding and prediction of material's performance.

* Intelligent Materials:
A huge improvement in performance safety and reliability could be achieved by developing materials that can sense, respond, and/or change properties in response to the radiation environment. These capabilities would revolutionize materials performance.

Diagnostic and monitoring methods, regulatory support

A second major grouping of required research involves research areas that primarily relate to current plants, but would also provide benefit to any future plant. These group includes topics such as: developing reliable models and codes to reduce the uncertainties in safety and reliability issues; providing methods for DOE and NRC to work together in developing research-based data and information on licensing issues, without compromising the NRC independence; making regulations
amenable to future designs and innovations, and developing a research base to support license approval for specific DOE missions. Specific research areas include:

* Digital Systems Instrumentation and Control:
Signal diagnostics and analysis, in-situ performance monitoring, failure prediction.

> Improving the ability to sense component and system performance parameters, reducing the uncertainty in performance parameters, improving the information obtained from sensed signals, and improving the ability for operators to interpret the meaning of signals would all improve plant reliability and performance. Reducing the uncertainties associated with data that supports a safety analysis would increase the efficiency by reducing unnecessary shutdowns. The ability to predict which components need replacing prior to plant shutdown (instead of during the shutdown) would save much time and resources.

* Virtual Knowledge Management:
Knowledge management needs fall into two basic categories: 1) the ability to access larger quantities of data while intelligently processing and managing this data to provide the operator with the optimum data stream, and 2) the ability to retain and transmit a knowledge base developed over years of plant operation to future generations of plant designers and operators. Knowledge management systems may be prohibitively expensive to retrofit into current plants, but would be valuable to future plant design.

* Plant Modeling and Simulation:

Plant performance, safety, and economic performance could be improved by developing a system that could provide predictions of individual component performance and integrated plant operations. These models need to be able to handle uncertainty analysis and provide accurate assessments of safety margins.

* Remote Technologies:

The ability to remotely monitor, operate, and repair components will increase safety by reducing radiation dose to employees and also improve economics by reducing the number of employees needed. Research into remote and robotic systems is required to provide these capabilities.

* Risk Informed Regulation Support:

Reactor plants can improve their economic performance by operating within a risk informed regulatory structure. Because this structure is fundamentally different from traditional regulatory practice, research will need to be done to improve the ability to define and quantify the risk associated regulatory imposed requirements. Weaknesses in the current technology database feeding probabilistic risk analysis must be addressed. Examples are human performance modeling, probabilistic risk analysis, common cause failures, and non-loss of coolant accident transient analysis.

* Regulatory Support for DOE programs:
Tritium production, MOX fuel

> Certain DOE missions such as tritium production and MOX fuel production require research to provide a basis for the regulatory system. Because these projects are unique to DOE, DOE will need to do the research necessary to support the projects.

Appendix G

Working Group Report on – Advanced Instrumentation/Controls/Simulation/ Operational Aspects

Nuclear Energy Research Advisory Committee

Subcommittee for Long Term Planning for Nuclear Energy Research

Summary Report
Instrumentation and Controls/Simulation/Human Factors Working Group
December 8-10, 1999 Workshop

Instrumentation and Controls/Simulation/Human Factors

Summary Report

December 8-10, 1999

Working Group Participants:

Steven Arndt -, Nuclear Regulatory Commission
Dennis Berry, Sandia National Laboratory
Mark Bryden, Iowa State University
Doug Chapin, MPR Associates
Beverly Hartline, Los Alamos National Laboratory, Breakout Group Leader
Carolyn Heising, DOE-NE and Iowa State University
John Lee, University of Michigan
Marty Martinez, Jupiter Corporation
John O'Hara, Brookhaven National Laboratory
Ted Quinn, MDM
Mark Strauch, Lawrence Livermore National Laboratory
Dave Weber, Argonne National Laboratory
James White, Oak Ridge National Laboratory*

I. Summary

The breakout group was charged to identify and recommend R&D needed to enable the use of advanced instrumentation and control (I&C), simulation capability, and virtual reality in the design, construction, and operation of nuclear power plants over the next 20 years. The group was to identify both human factors (including interface issues) as well as technical issues associated with these technologies. In addition, we were asked to provide advice on the appropriate role for the DOE and NE in the effort.

These rapidly advancing technologies offer enormous potential for improving the safety, reliability, proliferation-resistance, and economics of nuclear power. Benefits should accrue to the current fleet of plants as well as to Generation III and IV. With the new knowledge, capability, and advanced technologies that should result from the recommended research, it is conceivable that eventually nuclear power plant control rooms could have many "Star Trek Bridge" features, with operations and maintenance supported by high-fidelity, real-time simulations and accurate measurement of all parameters of interest.

However, nuclear power is a conservative, capital-intensive, and safety-regulated industry. The inherent time scale of product development and obsolescence in digital-based technology and instrumentation (~18 months) is very short compared with the multi-decade lifetime and investment-recovery period characteristic of a nuclear plant. How to mesh these time frames, adapt/develop devices and simulation models to nuclear-plant requirements, achieve demonstrable fail-safe performance from systems built using these technologies, guide updating of the regulatory framework and licensing criteria, and attract talented people are among the

* Unable to attend, sent contributions

challenges the suggested R&D addresses. It is encouraging that the Nuclear Regulatory Commission is currently receptive to improving the regulatory framework without compromising public health and safety.

Several important long-term research topics are identified and summarized in this report. There are many overlaps and interfaces between the recommendations and conclusions of this breakout group and the others at the workshop. Thus, we urge DOE, other sponsors, and proposers to integrate advanced I&C, simulation, and human-factors aspects into research programs and projects focused on the subjects addressed by other breakout groups at this workshop. We present the R&D recommendations in six major areas:

- **Crosscutting Issues**: regulatory-related research; R&D supporting technical standards, hardware interfaces, and reconciling the mismatch in time scales between nuclear plants (decades) and digital technologies (~18 months); advanced R&D infrastructure; and education and training.
- **Advanced-Instrumentation** research to adapt, develop, and/or validate: robust communications; wireless, high-accuracy, inferential, radiation-hardened, micro-analytical, and 'smart' sensors and devices; signal handling; condition monitoring; and the use of commercial, off-the-shelf equipment.
- **Controls and Control-Room** R&D to enable: fully integrated control rooms; adaptive automation; advanced diagnostics and control algorithms; better informed operator decision making; and safe operation of 'hybrid' I&C systems as existing plants replace analog with digital technologies in a phased manner.
- **Operations and Maintenance** research to advance: condition-adaptive maintenance and operations; on-line monitoring and robotic maintenance; virtual reality and simulation support for maintenance planning and operations; and 'self-healing' systems.
- **Modeling and Simulation** research to develop and confirm: high-fidelity, integrated, phenomenological, multi-physics, large-scale, and/or virtual-reality computer models; real-time simulation tools; and statistical models for component reliability.
- **Human-Factors and Human-Machine Interface** studies to guide the design of effective human-system interfaces (HSI) and to advance the fundamental knowledge base on human factors relevant to nuclear plant operation, maintenance, and training. DOE-NE has a role in future R&D related to the I&C/Simulation/VR/Human Factors areas.

Priority should be placed on topics and projects with the greatest potential to save money or solve a problem while maintaining safety and reliability. DOE's role should be to catalyze partnerships and collaborations (including international ones) and to sponsor or cosponsor R&D with significant societal benefits that won't happen without government involvement, due to risk, long-time horizon, or inadequate economic benefit for a commercial sponsor. A very important role is to fund (or cofund) the development of software, facilities, and knowledge that should be available to and shared by all stakeholders, rather than held on a proprietary basis for the economic benefit of its owner.

This report first proposes a long-term goal and vision for nuclear-energy-related R&D on instrumentation, controls, simulation, and operations. It then discusses the context and barriers for the R&D and the use of these advanced technologies in NPPs. The largest section describes several example R&D topics and subtopics that emerged in the working group's discussions and brainstorming. The final section addresses the niche for DOE in these efforts. The topics described are representative of promising research, but do not intend to be a complete listing. This report provides a basis for discussion and will be used as one of many sources for a long-range R&D plan being developed under the auspices of the Department of Energy's (DOE) Nuclear Energy Research Advisory Committee.

II. Goal/Vision

Information technology, sensors, instrumentation, communications, simulation, numerical models, and information management and display are advancing rapidly and offer a potential for adoption and/or adaptation for use in nuclear power plants (NPP). The long-term goal for NPP-related R&D on these technologies is to improve the safety, reliability, and cost-effectiveness of the plants. The R&D effort proposed by the working group is sufficiently broad that benefits should accrue in plant design, construction, operation, maintenance, and decommissioning. It includes parallel attention to the regulatory framework and process along with advances that will evolutionarily or revolutionarily change the role and training of operators and their physical and behavioral interface with the plant. R&D and implementation of these fast-moving, state-of-the-art technologies, moreover, are likely to attract bright young people to careers in nuclear power.

Sample elements of our vision for the role of computer technologies, digital instrumentation, controls, advanced simulation, and human-factors knowledge in NPPs in 2020 include the following:

- ‘Star-Trek bridge’ control rooms with natural human interface and extensive automation;
- ‘Smart’ and self-healing sensors, components, and subsystems enabling robust, inherently validated operations and monitoring;
- High-fidelity and real-time simulations and virtual reality to support design, operations, training, and maintenance;
- A new regulatory environment that ensures safety yet meshes with the innovation time scale inherent in high technology;
- A ‘learning system’ in which the people, technologies, and the information systems associated with nuclear power continually expand their capacity for safe, reliable, and cost-effective operations; and,
- R&D on any NPP topic routinely includes appropriate efforts on instrumentation, controls, simulation, operations, maintenance, and human-factors.

The R&D program to achieve the vision includes synergistic and coordinated efforts sponsored by DOE, industry, and international or foreign organizations. The R&D would:

- Focus on Generation II, Generation III, and Generation IV NPPs, thereby promoting both retrofittable and revolutionary advances;
- Leverage the considerable industrial, Federal, and international investment in fast-moving information technologies and instrumentation;

- Develop an updated regulatory framework and the technical data needed to support it, that would reduce the time and cost of obtaining initial regulatory approval for innovations in these areas;
- Include human-factors R&D to establish the knowledge base needed to advance operations, maintenance, training, qualification, and the control room; and,
- Build, integrate, and validate simulation codes and reactor-systems and physics models to support applications ranging from real-time decisionmaking to physically detailed, extremely high-fidelity simulations.

Section IV presents the R&D topics and subtopics recommended during the working group meeting. This presentation makes no assumptions about who should sponsor or perform any particular research. We urge that the R&D portfolios of the various players (DOE, other Federal agencies, industry, international and foreign organizations) be well coordinated, and that as much as practical the performers and projects be selected using a merit-based, competitive review process. In Section V we discuss our view of the appropriate role of DOE as a key research sponsor.

III. Context: Drivers and Barriers

R&D to provide and apply advanced instrumentation, controls, simulations, and human-factors knowledge to NPP is driven primarily by the very significant potential of these technologies to increase safety and reliability and lower construction and operations costs. Many hundreds of billions of dollars per year are invested by industry and government in the underlying information and sensor technologies. These investments are producing ever-more capable, inexpensive, fast, and reliable devices and ways to use them.

- Nuclear-specific aspects of the advanced information and sensor technologies, such as fail-safe components and architectures and radiation hardness, can be pursued and demonstrated comparatively cost effectively, building on the fast-moving technology base.
- Computer hardware, software, and information processing are sufficiently capable now to offer real advantages to NPPs. Faster and more powerful computers and more faithful and complete simulation codes would provide opportunities for calculations that are fast enough to support plant operations in real time and to improve their design, modeling, and licensing basis. Qualifying the codes and simulations through the regulatory process might not be as straightforward, however.
- The Nuclear Regulatory Commission (NRC) today is unusually receptive to developing new improved ways of doing business.
- With more detailed, timely, and accurate measurements of plant performance, operations and maintenance could be more solid and fact-based.
- The use of computers, thoroughly validated simulation codes, and sophisticated databases could help ensure that the experience and wisdom learned across the industry and throughout a plant's life would be available in real time to support design, operations, maintenance, and decommissioning decisions.
- The field of human-factors research is sufficiently mature that systematic understanding of the role and behavior of people in normal and emergency situations can be developed and applied.

However, nuclear power is a capital-intensive and safety-regulated industry in an economically newly deregulated business environment. The inherent time-scale of product development and obsolescence in computer technology and instrumentation is very short (order of 18 months or less). Yet the recovery period for the very substantial capital investment in an NPP and the plant's planned lifetime are very long (order of several decades). In this context, several barriers and conflicts emerge:

- The tension is considerable between the need for robust, maintainable standardized components and the opportunities to improve performance by utilizing rapidly advancing, state-of-the-art devices. How would one maintain a plant when component manufacturers continuously replace their product lines with new, 'upgraded' models?
- The conservative regulatory environment imposes a large burden to qualify components and plant changes, with the typical licensing time likely to be longer than a particular model of a digital component that might be available. A regulatory framework that truly assures safety while qualifying new technologies, configurations, and components as rapidly as they emerge in the electronics industry would be extremely difficult.
- Digital technologies do not yet have the reputation for fail-safe performance demanded of any NPP overall, and its systems, subsystems, and components separately.
- To do the necessary R&D and to implement the resulting improvements will require recruiting bright, talented people with expertise in these fast-moving fields. Such people already have a broad range of exciting and lucrative career prospects.

IV. Priority R&D Topics

For the purposes of identifying promising R&D topics and subtopics, the Breakout Group has organized this section into six major areas, where research would resolve key issues, develop the needed knowledge base, or make the adaptations required for the nuclear-plant environment. In fact, there is a lot of overlap and interaction between and among these areas. It was hard to sort the topics uniquely into the six areas, and many research projects that might be proposed would fit into more than one area. The R&D areas used for structuring this report are:

- Crosscutting Issues
- Advanced Instrumentation
- Controls and Control Rooms
- Operations and Maintenance
- Modeling and Simulation
- Human Factors and Human-Machine Interface

Cross-cutting Issues

In the breakout group discussions, after brainstorming R&D needs in each of the five technical topic areas, we considered whether important research would be missing because it either overarches or falls between the chosen categories. The answer was 'yes:' regulatory issues, standards, R&D infrastructure needs, and human-resource issues. This section mentions these 'orphans.'

1.) Regulatory –Related R&D

The legal framework captured in US NRC and industry codes and standards that govern many of the details of nuclear power design, construction, and modification was developed as the industry was developing and fielding the Generation I and early Generation II reactors. The technical basis comes from the collective wisdom and experience of the engineering and scientific community, heavily weighted toward what was known at that time. Design margins (e.g. cable sizes, levels of redundancy, piping thickness, and so on) are often quite prescriptive and not easily changed. Most of the general regulatory principles, such as the single-failure criteria, as well as the specific regulations, were developed long before the advancements that high-speed digital electronics would bring to modern I&C were known. Although a promising new technology (e.g. an addressed condition-monitoring sensor or an analysis code) may justify a reduction in a design margin, the reduction cannot be implemented until it is incorporated in the governing codes, standards, and regulations. R&D needs to be conducted to determine: (1) where today's codes and standards prevent the use of advanced I & C/simulation/operations, (2) how they could be changed to be more applicable to digital I&C without compromising plant or public safety, (3) how the regulatory framework of the future should be configured to facilitate the adoption of rapidly advancing technologies, while continuing to assure safety, and (4) the technical information and metrics needed to permit regulatory acceptance of these new technologies.

In addition, research is needed to ensure that methods for regulatory validation and approval of new technologies are available by the time the technology is ready to be considered for licensing. Another effort should establish the knowledge base for an appropriate new benchmark or set of regulatory approval criteria for Generation IV plants. For instance, the accident analysis would not be the same for Generation IV as for the earlier generations because the transient response in Generation IV is a lot slower.

Research is also needed to guide the regulatory approach to hybrid control systems that will be in place when current plants upgrade from analog to digital systems in a phased manner over many years. The current sets of regulations are essentially in either of two forms: an older set based largely on analog equipment and a more recent set based primarily on digital technology. Hence, regulatory guidance is available for either part of the hybrid system but not for how to ensure safety when a plant's I&C system makes extensive and transitional use of both types of technology.

2.) Technical Standards and Standardized Interfaces

The ability to infuse new technology and avoid the burdens of obsolete systems will be enhanced through the appropriate development/selection of technical standards and the development and adoption of versatile standardized interfaces. This need is exemplified, for example, by an anticipated evolution of sensors from the simple types supported by 4-20 mA serial loops to sophisticated devices with embedded computing running Java applets requiring a web-based interface over an ethernet connection. In many cases the standards and interfaces are implemented in the device industry, which serves many different applications. Research is required to identify existing and emerging standards that will materially impact future standard interfaces for NPP instrument and control systems, and to provide the knowledge base needed to participate in standards adoption and ensure they would be nuclear compatible.

3.) Reconciling the Inherently Different Timescales of Nuclear Power Plants and Modern Digital I&C Systems

As a result of the large mismatch between the timescales of NPP life times and digital technology evolution, it could easily be that the systems designed for use in a plant would be obsolete and in danger of reduced or abandoned vendor support before the plant is even operated. Certainly electronic devices and computers will go through many generations providing many-fold increases in performance during the life of a plant. Problems created in this environment include: loss of vendor support (spare parts and technical support and training, etc); increased cost to either maintain your own systems independent of the vendor or to keep changing out equipment as the vendor upgrades; undesirable and (and risk increasing) creeping functionalism as more features are added to the vendor's standard I&C systems which might not be needed in the plant; design-basis changes; and, licensing and training of operators and maintenance staff. It is unrealistic to expect that the nuclear industry will drive the I&C industry to match nuclear life cycles. Hence, an effective strategy must be created to deal with this fundamental mismatch in time scales. Research is needed to investigate various strategies and technologies to address this issue. Some topics will be hardware or software oriented, such as picking technologies, which can be easily replicated, or controlled or preparing the software and documenting it in a readily available form (*e.g*. the customer obtains and controls the original software for the system). Other research is more administrative in focus (*e.g*. to define how the plant design basis and regulatory guidance can be kept current more readily so that regulatory oversight can be effective but not act as an overly restrictive drag on the process).

4.) R&D Infrastructure

The R&D programs being proposed focus on reactor concepts that require a better understanding of identifiable physical phenomenology as well as understanding of new phenomenology present in alternative reactor designs. To be accepted by the public and licensing authorities, the critical concepts and phenomenology must be demonstrated both analytically/computationally and experimentally. Consequently, adequate experimental infrastructure must be developed to verify phenomenological and modeling predictions, to insure the correctness and adequacy of proposed designs and operating conditions, to contribute to the licensing basis, and to test new concepts in a safe, flexible, and extremely well monitored setting. The purpose of the research would be to identify infrastructure needs for the proposed research, then to construct and operate these experimental facilities. One attractive candidate would be a research center for advanced control room, human-system interface (HSI), and I&C technology development. Another one is a virtual-reality facility capable of simulating a plant or pilot plant with fully interactive, three-dimensional interfaces. In addition, university research reactors (URR) could be used to study many of the issues associated with incorporating digital I&C in NPPs. Although their I&C systems are comparatively simple, URR provide an environment complicated by the real-world problems of regulatory constraints and radiation. Thus, URR are attractive facilities for studying advanced control algorithms, HSI issues, on-line monitoring and diagnostic systems, and advanced instrumentation and sensors.

5.) Education and Training

The advanced R&D plan being developed by DOE/NE is focused on use of state-of-the-art and leading-edge technology for nuclear power plant design, analysis, operation and maintenance.

Clearly, to take advantage of rapid advances in instrumentation, sensors, materials, control, and simulation capability for the benefit of nuclear power, nuclear engineers, regulators, and plant operators will require specialized skills and knowledge beyond the traditional. In most of these areas, the nuclear-energy industry will be competing with other industrial and commercial segments for qualified talent. To realize the technical objectives will require attracting very talented young engineers and scientists. In addition, the technical capabilities of current researchers will have to keep pace with the state of the art. The objective of this research area is to identify and develop innovative and effective pedagogical approaches and instructional materials. Thus, the needed advances in education and training will be available to prepare personnel qualified to lead and support the research programs proposed here. Although it is not a research topic, in itself, human-resource recruitment and development is an important challenge in its own right, and will need attention.

Advanced Instrumentation

The broad topic of advanced instrumentation includes devices, sensors, along with means to communicate with them, maintain and replace them, and verify and use their information to support plant operations and maintenance. Many have been and are being developed for and used in other applications. The generic issues that need to be addressed for nuclear power plant applications include:

- The impact of these devices on nuclear safety, specifically their reliability, the need for redundancy, testing and certification of smart devices and embedded software, and the effects of radiation on the devices;
- Identification of specific applications where these devices have the potential for a significant positive impact on current problems, or could significantly improve plant operations;
- The development of standards and methods for nuclear certification of these types of components; and,
- How to verify and calibrate their signals *in situ.*

1.) Robust Communications and Wireless Sensors

Advanced instrumentation and control systems in power plants will be based on the use of large, integrated, distributed digital systems with many more and more advanced sensors and other nodes than present systems. For example, increased use of sensors will be of interest to provide extensive capability for condition assessment in components and equipment throughout the plant. Robust communication throughout the network will be crucial. Present systems employ physical cables to carry the signals and distribute power for monitoring and control functions. These cable systems are expensive to install, are subject to aging over long periods, and provide a vulnerability to common mode failures. Future plants will require a robust communication system that is easier and much less costly to install but still provides the necessary isolation and segregation of signals. Current plants are beginning to use optical fiber and some exploration of various wireless communication networks is being done. Research and development is needed to define and make practical a robust communication system to support advanced instrumentation control system applications in a power plant environment with its physical boundaries and structures, large metallic structures, varying electromagnetic fields and potential transients due to switching transients in power equipment and from external effects such as lightning. Current advanced digital I&C equipment available are already capable of producing signals that can produce upsets in other equipment (e.g., walkie-talkie signals can trigger undesired response in digital electronic equipment) and have susceptibilities to interfering signals from other equipment either through radiated or conductive paths. Operational restrictions, special shielded enclosures, and filters are needed to deal with these problems. The needed research program would identify potential robust communication techniques and architectures which could be used with high confidence in nuclear power plant applications to support large scale, integrated, distributed digital I&C systems which do not require the use of cabling for communication. R&D is needed to understand the performance and reliability of wireless systems under normal and accident conditions. These conditions include ambient EMI/RFI, harsh conditions that may degrade link bandwidth (e.g., steam, water, radiation) and susceptibility to unintentional/ intentional interference (e.g., maintenance crew transmitters and sabotage).

2.) Instrumentation for High-Accuracy Measurement
Instrumentation providing measurements of a higher accuracy than currently available is needed for some applications. One example is the need to measure water level more accurately than is currently possible. Another example would be to monitor neutron flux in a way that adjusts for temperature changes, boron concentration, and types of shadowing. This new instrumentation would have to be able to meet the qualification requirements for the Generation IV environments and safety classification.

3.) Inferential Sensing and Virtual Measurement
Instrumentation to measure a parameter directly often cannot be placed at the point of interest. Therefore, devices should be developed that compensate for the difference between the installed location of the instrument and the point of interest of the parameter or measure related parameters and accurately infer the parameter of interest. An example of such inferential sensing may be to use temperature to measure level (heated thermocouple is a current example) or accounting for the difference between an resistance temperature detector (RTD) located on the surface of a pipe and the measurement of the temperature at the center of flow in the pipe. This R&D may include the development of algorithms for processing signals from multiple sensors in several locations.

4.) Radiation Hardened Sensors
As sensors become more sophisticated (e.g., embedded electronics, micro-electro-mechanical systems (MEMS) structures) the need to understand the performance of such sensors in high radiation environments will increase. Conversely, the known radiation performance of certain materials may influence their inclusion in advanced sensor development. R&D should focus on material selection and device/structure integration to achieve high overall performance (accuracy, lifetime, etc) in a high radiation environment. Integration includes process-development research to enhance radiation resistance of assembled devices/structures/components.

5.) Use of Commercial Off-the-Shelf (COTS) Equipment
Much of the I&C equipment in current nuclear plants is custom hardware. This equipment is expensive to purchase initially, is expensive to maintain and introduces special burdens with custom training and maintenance activities. Further, since nuclear is a very small market, the

vendors tend to quickly lose interest in supporting this equipment. The commercial I&C market is huge and will follow its own directions so it will be imperative that nuclear plants be able to effectively use COTS equipment in their I&C systems. Utilization of COTS equipment will avoid becoming orphaned quickly, will take advantages of standard maintenance and support technologies, and will ease the problem of ongoing upgrades. Work is currently beginning on how to qualify COTS equipment for use in nuclear plants and the initial results indicate costs are still very high, and each application tends to be a custom assessment and a case-by-case qualification. R&D is needed to identify more clearly the critical attributes needed in COTS equipment to enable its use in nuclear applications, provide standardized techniques for carrying out the needed assessments, defining effective ways to supplement COTS design and testing approaches to meet nuclear standards, and working with the vendors and manufacturing groups to investigate whether relatively minor changes could be made in current commercial products and processes to support their use in nuclear service. For example, by coordinating efforts with other users of safety critical systems, such as the petrochemical industry, the military and the aerospace industry, a large enough market could be defined for common features which would make the use of COTS equipment easier and much more cost effective for all of the parties.

6.) Signal Handling

The assessment of plant status depends on an accurate measurement of actual plant conditions, normally provided by sensors in the plant instrumentation system. Such information is used to guide operator actions. When advanced control room, decision-making aides are available, some signals must couple into those aides and could be used to set status conditions and initial conditions for predicting system behavior and real-time 'what-if' analysis. The objective of this research is to develop techniques and software that can assure the operator and/or control system that the reported signals reflect actual plant conditions (on-line signal verification and validation). Additional studies would develop techniques that allow coupling of sensor signals to use as inputs for simulations that assist the operators. (See R&D topics in the simulation section). Such techniques should determine the consistency of multiple sources of related information, identify faulty sensor information, provide highest confidence initial conditions, account for uncertainties and fluctuations in the signals, and establish system and component status for use in the subsequent simulations. The transient management and control software should be designed so that unanticipated events and, to the extent possible, accidents of unknown nature could be properly handled so that the plant can be maneuvered to a safe operating condition or shutdown state. Development of software with these attributes will require advanced diagnostics and control (D&C) algorithms together with accurate simulation models that may offer both symptom-and function-based diagnostic information.

7.) Condition Monitoring

Many industries and industrial sectors are benefiting from advanced condition-monitoring technology, especially when conditioning-monitoring information is tracked and analyzed by reliability, safety, or maintenance software. Through the use of Smart Sensor signals, historical data, system-response models, and probability-analysis techniques, nuclear power plant operators and regulators can make more technically grounded decisions regarding maintenance schedules, safety margins, the need for unscheduled outages, and hardware upgrades. Furthermore, longer-term concerns (e.g. aging) and accident response options (e.g. equipment operability following a fire or earthquake) can be addressed through well-correlated and enhanced condition monitoring.

One of the technologies for condition monitoring takes advantage of a robust suite of imbedded sensor techniques that could be developed or adapted. Advanced microelectronics now enables the development and use of imbedded sensors in many locations here-to-fore not possible. These applications and locators include: strain measurements of structures and piping; corrosion of material; localized temperature, flow, pressure, and vibrational conditions; and localized electrical properties, among others. R&D topics range from the development and demonstration of embedded sensors and other technologies to issues associated with sensor powering, communicating, and integration over what may be a 60-year emplacement. Condition monitoring R&D topics include specific pH, insulation resistance, structural stress levels, and software and techniques for data integration and failure prediction.

8.) Micro Analytical Devices

Micro analytical devices are being developed that will provide low cost, highly reliable measurement of temperature, pressure, gas species, and other parameters. Because of the small size and low cost, these devices will be used for the development of smart components, and control systems based on real time analysis. It is likely within 5 to 10 years that these devices will link with the hardware (pumps, pipes, valves) in control and analysis systems and allow real-time analysis, predictive maintenance, and operator assisted control. Industries that are currently developing these types of devices include the automobile and the non-nuclear power industry. The R&D issues that need to be addressed for nuclear power plant applications include primarily the generic issues identified in the introduction to this section.

9.) Smart Instrumentation and Equipment

Today smart instrumentation and equipment typically are ordinary devices linked to an artificially intelligent control system. The smart systems of the future are likely to be significantly different. The smart plant will be built from smart components that provide a wide range of information and analysis to an analysis and control system. This analysis and control system will perform complete systems analysis, across multiple scales and systems utilizing real time, high fidelity, computational models to explore and find the optimum path for operation of the plant. This optimum will include a wide range of concerns (e.g. safety, ease of operation, efficiency, and cost). The goal of R&D would be to develop and qualify smart instrumentation and equipment for use in current and future NPPs. Smart instrumentation would be like "watchstanders," monitoring NPP components and systems. The key characteristics of a smart component include measurement and analysis of one or more parameters and decision making and action taking (e.g. forwarding the results for consideration by a larger system, taking the independent action, logging the results for future consideration, etc.)

Controls and Control Rooms

When NPPs were first developed, the challenge of controlling these enormous, complex, and hazardous systems led to the development of control systems and control rooms that defined the state-of-the-art. Since then, NPP control has remained reliant on the licensed, approved control concepts and hardware, which represent 1950s/60s technology and knowledge. Needless to say, breathtaking advances in computer hardware, software, control concepts, etc. have taken place in the intervening decades, to the advantage of manufacturing processes in many industries and for the control and operation of other power plants and a variety of large, complicated systems. Key among the generic R&D issues prerequisite to full use of the rapidly advancing information technology capability are the regulatory framework and associated standards (see Crosscutting R&D).

Controls and control rooms must link with plant-monitoring instrumentation, utilize models and simulations, and provide the interface to the operators. Thus, many R&D topics in the sections on instrumentation, simulation, and human factors are also relevant here, and *vice versa*.

1.) Fully-Integrated Control Room (aka: Star Trek Bridge)
Future nuclear power plants may be less-complicated and more forgiving (i.e. inherently safe), and it is reasonable to expect that new control rooms will evolve to help simplify operator decisions and actions through automation, expert systems, condition monitoring, accident assessment, decision support software, and “man-machine” interfaces (e.g. GUI’s). At one end of the spectrum is the control room of today, with many different gauges, switches, meters, and controls that an operator learns to deal with. At the other end of the spectrum is a nearly featureless control room that more or less runs entirely on autopilot without any significant operator action required. However, it is not clear what the optimum control room should look like and how it should interface with operators. There are many opportunities for innovation, especially if a 10- to 20-year horizon is considered. Research should support the development of a control room providing a fully integrated information and control system. The control room would break away from the tradition of separate human-system-interface (HSI) resources for alarms, information, procedures, support systems, and controls. Instead, these systems’ functions will be integrated into an HSI supporting plant monitoring, detection of disturbances, situation assessment, response planning, and response execution by a combination of crew members, intelligent agents, and automatic systems. The goal of the research will be to develop an interface between plant and personnel, that provides information to the crew in a way that operators get information effortlessly, when and where they need it, and in an immediately understandable format. The interface will provide error tolerance, i.e., minimize human error and provide a means to detect and recover from errors when they do occur. R&D topics could explore the feasibility and benefits of voice commands/ questions, database management, and automated action without human involvement, while addressing issues of safety, reliability, and human factors.

2.) Real-time Analysis to Support Operator Decision Making
Currently all operations in NPPs are, in part, human-in-the-loop operations. This situation is similar to many activities, e.g., driving a car, in which human intervention and decision making are key components of safe operation. The key difference that will be developed in many industries during the next 10 years is that these human decisions will become more informed. Instead of reading a pressure, flow rate, and temperature and deciding on the course of action, the operator will have available a wide range of analysis and real-time simulation tools to aid these decisions. "Real-time" refers to analysis that enables the operator to ask questions/perform analysis and receive the results without delay, that is in real-time (~1-10 seconds). These systems will extend beyond artificially intelligent and neural net approaches and will be based on the fundamental physics of the systems involved. They will include the impact of coupling multiple scales and multiple systems together to predict unforeseen events, and to explore the full range of possible operational paths available. Plant simulators already are designed to

provide a predictive capability of the system, given a set of initial conditions, a sequence of operator actions, and the evolution of individual systems and components. If such simulators were to become capable of predicting system behavior under a broad spectrum of scenarios and if they are able to run in real time and/or faster than real time, they offer the opportunity of being a decision aid to operators to supplement normal procedures and augment procedures under off-normal and unusual accident conditions. One objective of this research is to develop real-time simulation and analysis capability that can accept plant condition information as initial conditions and provide real time/faster than real time prediction of system behavior under hypothetical operator actions and expected system response. Techniques for simulator software verification and validation should be addressed. Humans would still be making key decisions, but they would be better informed than is possible at present.

3.) Digital System Reliability, Fluctuations, and Failed Sensors

The technology and methods to improve how we measure and assure reliability of digital systems (both software and hardware and how they interact) when used in nuclear power applications, are of critical importance to the continued application of these systems in NPPs. The current regulatory structure requires that new systems that are introduced into NPPs undergo an extensive and very expensive review by the NRC unless it can be shown that they do not introduce any unresolved safety issue or new failure modes. The current state-of-the-art in digital systems (both software and hardware and how they interact) is not at the level that clear predictions of system reliability can be developed for safety applications with any level of certainty. Because of this limitation the use of digital systems has been greatly limited in the NPPs in the United States (mostly in support systems).

Additionally, the lack of an effective way to measure reliability of digital systems in nuclear applications introduces significant uncertainty into the analysis of these systems in a Probabilistic Risk Assessment (PRA). This uncertainty associated with the lack of models requires that additional margin and redundancy be included into the design of these systems for NPP applications. Because the issues associated with obsolescence, slow wearing out of original I&C equipment, and the potential improvement in capability and reliability of new digital systems, it is imperative that the research into the measurement of digital system reliability be carried out, and that the particular issues associated with nuclear application of the technology, be included in this research.

4.) Distributed (remote) Computing, Control & Monitoring

Classic I&C Systems employ distributed sensors of, at best, modest intelligence arriving to a central control and monitoring point. Future systems will deploy much more advanced sensors embedding substantial computational capabilities. Such capabilities give rise to the ability to distribute, possibility in real time, the computations required to affect control. In addition, the exercise of control can be similarly distributed, and may pose interesting situations and possibilities. Experts can be consulted remotely for unusual situations. Expert teams may control multiple plants. Very highly qualified crisis teams may assume control (remotely) from steady state operation teams in time of need, for example. Remote monitoring may contribute to increased transparency of operations, especially to advance non-proliferation objectives. Research is needed to identify and solve NPP specific issues related to distributed computing, control and monitoring. These include, for example, reliability of self-forming networks of intelligent sensors and computers under failure and accident conditions. Embedding/distributing control algorithms and ensuring that real time control objectives are met, especially over the span of NPP operations, represent significant research opportunities.

5.) Adaptive Automation

The proper mix of human involvement and automatic systems will help ensure overall human-system efficiency and reliability. This research will use the fundamental knowledge developed addressing automation to support the research into the design of better integration of personnel and automatic systems by addressing the problems associated with having operators "out-of-the-loop." These problems include operator loss of vigilance, extreme workload when automation systems fail, and loss of skill in performing control tasks. Such a system may provide for variation in the degree of automation and manual control to best achieve overall human involvement and performance.

6.) Advanced Diagnostics and Control Algorithms

In the control room for future NPPs, advanced software for D&C maneuvers will play a major role together with other features that will provide an efficient and error-free human-machine interface. The D&C software should incorporate, in an integrated framework, artificial intelligence (AI) approaches, including artificial neural network (ANN), fuzzy logic, and expert system, for diagnosis of transient events and monitoring of incipient component failures. Although these tools have been used in a variety of diagnostic applications separately, significant development and optimization effort will be required to integrate them so that key features of the AI approaches can be capitalized to yield a synthesized diagnosis. Likewise, ANN and fuzzy logic have been used individually in control studies, but little effort has been made to date to integrate these AI approaches with modern control theory algorithms in a synergistic manner. In particular, recent advances made in model-based control theory, in particular, *H-inf* control theory, should be considered. The *H-inf* ? control algorithms provide robust, stable control maneuvers and can effectively account for uncertainties in system models and at the same time reflect the desirable system performance in an integrated fashion.

7.) Hybrid Systems

There are approximately 100 nuclear plants in operation in the US. These plants were designed more that twenty years ago, and even the most modern ones do not make extensive use of up-to-date digital I&C systems. Furthermore, these plants are valuable assets to their owners, who optimize their economics by operating them for long periods (18 to 24 months) with short shutdowns (3 to 4 weeks). Upgrade of these plants to modern digital systems will certainly take place as the plants continue to age. Given the cost of the upgrade, the degree to which the I&C systems are intertwined in the plant, and the short windows of opportunity to do the upgrade work, the change-outs will take place gradually. As a result, the plants will operate with hybrid systems that are a mixture of up-to-date digital technology and older technologies. Research is needed to understand how to design and phase the upgrades and to provide the knowledge base needed to operate and maintain hybrid installations safely.

Operations and Maintenance

Effective operations and maintenance are major drivers for the safety, reliability, and economics of nuclear power. The supreme importance of safety demands very conservative operations and maintenance practices. Research should enable the development of a risk-informed approach to maintenance planning. The ability to calculate risk in real-time on the basis of known, accurately determined plant and component condition would provide a useful guide for plant-wide maintenance activities. Furthermore, simulation capability and/or virtual reality could help in the development of operations and maintenance procedures and provide training. Please see also several R&D topics described in the instrumentation section.

1.) Condition-Adaptive Maintenance and Operations (CAMO)
Condition-monitoring sensor technology and software systems can provide the information plant operators and regulators need to make reliability and risk-based decisions for plant maintenance and operations. However, a system representation (model or simulation) of the plant must be integrated with the sensor data and trending information to support the decision process. Ideally, maintenance is performed just before a failure occurs, and operations are carried out at or near the full capacity of systems and equipment. If this could be done safely (without excessive margin), then power generation would be most efficient. R&D could help establish how and to what extent advanced hardware, software, and systems modeling could incorporate CAMO into existing and new-design power plants. As conditions change within plant equipment and systems, maintenance schedules and operation could be modified and optimized.

2.) On-line Monitoring
Research should be conducted to support on-line monitoring, fault detection, situation assessment/diagnosis, and response planning through the use of advanced instrumentation and computer and computational technology. The challenge is to enable the systems to perform difficult cognitive tasks and be fully integrated into the operational environment. R&D is needed to replace some calibrations and to demonstrate higher reliability of the equipment by quicker diagnosis of failure or degradation beyond operability requirements.

3.) Virtual Reality for Maintenance Planning and Operations
Virtual reality is rapidly becoming an accepted design, operation, and maintenance tool in many industries. It provides a mechanism for creating a three-dimensional, virtual power plant that accurately represents plant systems, components, and operating conditions. In the case of non-routine and/or complicated procedures in normal operations and maintenance, a virtual test bed can help to develop the procedures, test them and train plant staff. The objective of the research would be to develop a virtual system that would represent the actual plant and/or component environment. In addition, techniques and technologies should be developed that allow staff to interact effectively with the virtual world, incorporating simulation of real-world feedback and consequences. (Please see more extensive write-up in the Simulation section.)

4.) Simulation for Maintenance Planning
Maintenance, certification, testing, and startup are significant cost drivers within the nuclear industry. Often the shutdown is extended due to interference between jobs, unexpected work, or misunderstanding between work groups. Simulation software should be developed that enables

the user to schedule maintenance, train workers, examine the work to be performed at any given moment, adjust plans to avoid interference, and consider the impact of unexpected problems. The research issues include the development of methodologies and algorithms for maintenance planning, the development of complete, low-cost, three-dimensional models of plant components, and coupling these models to the design and operations models (see simulation section).

Benefits would include reduced downtime and reduced exposures to crews for tasks performed in hot or dirty environments.

5.) On-Line Robotic Maintenance
In many cases NPP maintenance must be performed off-line. The use of robotics may allow on-line maintenance of some systems, allowing shorter outage times and lower personnel exposures. Research is needed to identify systems, structures and components conducive to robotic maintenance, change NPP design to facilitate such maintenance (e.g. access and workspace), and develop robotic capabilities unique to nuclear servicing requirements.

6.) Self-Healing Systems
Moving past smart sensors and components, long-term research is needed to develop components and systems that have self-healing capabilities--i.e., they repair themselves. Today, work is being done on self-configuring computers that avoid damaged areas. In the future, the types of self-repairing systems should be expanded, for example, by creating novel materials that heal surface defects and avoid corrosion, or by devising automated annealing processes that achieve and maintain desired material properties guided by embedded sensors.

Modeling and Simulation

The design and operation of NPPs involves multiple interacting, dynamic, and time-dependent factors and phenomena. Current analysis and design codes were developed 10 to 30 years ago, when computers and computational algorithms were orders of magnitude less powerful than they are today and our understanding of nuclear plant phenomena was less mature. It is now possible to conceive of codes that incorporate realistic phenomenology, integrate all the relevant physics and engineering, couple between micro-scale and macro-scale processes, and/or that can simulate plant behavior in real time (or faster). In addition, modeling technology could be advanced to allow the use of the same model from birth of the plant concept, through design, construction, licensing, maintenance and operations, and to decommissioning. Virtual-reality simulations could become valuable tools for plant design, licensing, severe-accident analysis, operations, and maintenance. Several promising long-term research areas are suggested here.

1.) High Fidelity Phenomenological Simulation
Certain critical phenomena are important in determination of plant operating conditions, operational limits and facility and component life. This phenomenology is often represented in a simplified manner in analyses that are used in setting operational limits and lifetimes. In some cases, more accurate prediction of the physical phenomena may identify overly conservative limits to plant operation and lifetimes, suggesting the possibility of operating the plant more

economically and for longer times, without sacrificing safety or reliability. Advances in physics models and computational capability are becoming available that permit a first-principles assessment of such phenomenology. The objective of this research would be to select specific phenomena, develop appropriate mathematical models and advanced computational techniques, verify and validate the capability to predict the phenomena, and make the developed computational tools broadly available.

2.) Multi-Physics Simulation

The operation of nuclear power plants involves multiple interacting phenomena, which are typically examined on an individual basis or coupled together in an approximate systems analysis framework that was state-of-the-art at the time of its development in the 1970's and 1980's. In some cases, a higher degree of modeling capability has developed for the individual phenomena, but the questions of interest are related to the interaction of these phenomena. The objective of this research would be to identify areas where coupled effects are critical and to develop mathematical and computational techniques for the integration of these high fidelity models to examine tightly coupled systems. Some promising areas include: fuel-failure models, severe-accident models, material-damage models (under much higher temperatures), thermal-fluid models in much different ranges of temperatures and for different fluids, and human-cognitive models. These programs are expected to take advantage of recent and ongoing advances in numerical algorithms, mathematical software and high performance computing technology.

3.) Large-Scale, High-Fidelity Integrated Systems Analysis

Under normal, off-normal and accident conditions, NPP performance involves a complex set of interacting systems, components and phenomenology. The computational infrastructure exists today to run higher fidelity models of important phenomena, examine complex interactions, and include greater fidelity in the representation of critical systems and components. Such a comprehensive and integrated plant representation could help to quantify the conservatism in operations and identify the potential for enhanced economics, while maintaining or improving safety and reliability. The objective of this research is the development of the next generation of systems analysis codes, which take advantage of developments in mathematical modeling, numerical algorithms and high performance, massively parallel computing. In addition to the development of accurate first-principles simulation models that may represent short- and long-term behavior of the entire NPP systems, effort should be made in the near term to develop integrated software that merges a number of existing systems codes in an efficient and consistent manner. One such example could be the consolidation of the RELAP-family of codes, for primary loop dynamics, with the CONTAIN-family codes for containment behavior. Another example would be the coupling of PRA simulations with thermal-fluid simulations to allow direct analysis of the effects of failure criteria and substantially aid reactor design. This research area should also address mathematical and computational issues associated with describing interacting phenomena with potentially large differences in time scales, the interpretation of large amounts of computed data, the role of scientific visualization technology and the verification and validation of the resulting models.

4.) Statistical Model for Component Reliability and Degradation Monitoring
One of the key incentives for implementing advanced I/C technology in future NPPs will be the ability to detect and identify degradations and incipient failures in plant components and systems. This ability will be of critical importance in prioritizing maintenance during the planned outages or for performing online repairs as needed. This will obviously help reduce the outage time and hence the operating cost, and would be of considerable benefit in risk-informed maintenance approaches, even for the current generation of NPPs. For this purpose, component reliability data, in proper statistical structure, could be used together with accurate simulation models to provide the component degradation monitoring capability.

5.) Combination of Simulation Models and I&C Algorithms
Implementation of advanced diagnostics and controls (D&C) software in future NPP control rooms and I&C applications will benefit significantly from the use of accurate simulation models. The *H-inf* control theory requires a simulation model as an integral part of the overall algorithm, although the control algorithm is structured to account for a certain degree of uncertainties or deviations from reference predictions. Statistical approaches for component degradation monitoring would also require plant simulation models. For these D&C purposes, the simulation models should be developed so that the full-blown first-principles capability of a high-fidelity NPP code may not be required. Instead, component-level simulation models of sufficient fidelity could be structured to yield efficient interfaces for various D&C applications. The interface between detailed nonlinear simulation models and D&C software should in general allow for dynamic structure as the system evolves in a particular event and different components of the plant begin to play more dominant roles in the system dynamics.

6.) Real-Time Simulation
Real-time simulation uses numerical models based on the fundamental physical principals of the process involved that run fast enough to permit real-time decision making. Currently, several simple real- time models link thermodynamic properties, equations of state, and the conservation equation of energy, mass, and momentum to develop an understanding of how global changes affect plant operation. This capability needs to be extended to include detailed models of fluid flow and heat transfer to provide accurate real-time simulations, achieving the detail available in computational fluid dynamics and finite element analysis of stress and heat transfer. These models will enable smart control systems, virtual power plants, operator informed decision making, and will enable coupling across a wide range of scales and systems.

The key research issue is the development of methodologies and algorithms to allow real-time analysis of system performance. Faster, bigger, less expensive computers will help enable the analysis but are not the solution for developing real-time simulation capability. The software must be able to couple various systems together, calculate only those regions and systems affected, and determine the accuracy of the calculation, plus provide the results to the operators in an instantly understandable way.

7.) Virtual Reality
Virtual reality describes a variety of experiences ranging from three-dimensional visualization to fully immersive and interactive synthetic environments. As used here, "virtual reality" is a three-dimensional, computer-generated environment that the user can move around in, view from many different perspectives, interact with, and modify. When coupled with an expert in the area

of interest (e.g. a manufacturing engineer, an architect, or a medical doctor), virtual reality can catalyze breakthroughs in our knowledge and understanding.

Key aspects of the virtual experience include immersion and interactivity. Immersion refers to the degree to which the individual is fully encompassed within the virtual environment. Interactivity refers not only to the degree that the user can move around and change perspective, but also to the degree that the user can change and mold the environment. This capability to interact with the data holds significant potential. The user could physically alter a component in a virtual power plant and see the impact of this change on the system. For example:

- A design engineer could change the size of a pipe and see the impact on the flow in the system.
- The construction path for a plant could be completely laid out and explored by all the affected groups, reducing the construction time and interferences between component installation.
- The design of a heat exchanger could be examined by altering the geometry, thickness, or spacing of any or all of the components and would immediately see the changes in heat transfer and fluid flow on both sides of the heat exchanger.
- A trained operator could examine the fully three-dimensional flow pattern within the core noting any changes from the expected.

Virtual reality also provides a tool through which information can be examined and shared at a variety of levels. For example, an engineering team based in a number of geographical locations could interact directly with the virtual pilot plant at a number of locations simultaneously and to see the results immediately.

Research specific to nuclear power would include the development of virtual models of components, of real-time simulation capability for plant operation, and of the human-machine interface.

Human Factors and Human-Machine Interface

1.) Human-System Interface

The Human-System Interface (HSI) is composed of numerous resources including alarms, displays, procedures, support systems, and controls. These resources are integrated into workstations and control rooms (and other facilities, such as remote shutdown stations and technical support centers). In current control rooms, there is a limited range of devices used for HSIs. For example, plant information is largely displayed on strip charts, meters, gauges, simple digitized numeric displays, and simple computer graphics, such as, mimic displays. Computer technology offers great power to improve these interfaces. For example, plant parameters can be integrated in computer graphics forms, such as graphic displays based on the Rankine Cycle, intended to present information at a higher more usable level. Processing of lower-level information can be done by a computer not by the operator. Research is needed to define appropriate application of the technology and to develop guidance so the HSIs do not confuse operators and lead to increased error.

2.) Developing Fundamental Base of Knowledge on Human Factors
One roadblock to successful integration of personnel into advanced systems is our limited knowledge about the human processes involved in NPP monitoring and control. Such research will form a technical basis to greatly advance the design of control rooms and the interfaces used by personnel to perform their rolls. This research would build on and complement human-factors knowledge developed in other environments. Key examples of such research topics include:

- Understanding the relationship between automation and operator vigilance, confidence, and ability to assume control when automation malfunctions. This knowledge will contribute to the development of more "operator-friendly" automation and considerations of staffing reduction.
- Understanding of the cognitive process used by crew members to perform situation assessment, diagnosis, and plan responses. This will support the design of better displays, procedures, and operator support systems.
- Understanding how teams best function, communicate, and coordinate their activities. One of the significant effects of advanced technology is on crew interaction. This research will help to develop advanced control room with appropriate design for crew interaction, communication, and coordination.
- Understand how crews handle events that are unanticipated by designers, unplanned, and for which operators are not trained. Better understanding of how crews can handle such “beyond-design-basis accidents” can lead to improved procedures and HSIs, and reduce the risk associated with such complex events.
- Understanding how training will have to be changed to address the effects of advanced technology and the changing human role in new, more advanced plant designs. Also, research needs to address how advances in training can lead to more effective training for operations and maintenance crews.
- Understanding the relationship between technology and human error mechanism. This research will lead to advances in the design of error relevant systems (in *** error reduction, error detection, and error recovery).

V. Recommended Role for DOE

DOE’s role is to sponsor R&D with significant societal benefits that won’t happen without government involvement, due to risk, long-time horizon, or inadequate economic benefit for a commercial sponsor. A very important role is to fund the development of software, facilities, and knowledge that should be available to and shared freely by all interested parties, rather than held on a proprietary basis for the economic benefit of its developer/discoverer. DOE could use its available infrastructure and other venues for demonstration of initial R&D applications (for example, its nuclear and accelerator facilities and projects, nuclear material management and control systems, university research reactors, and international resources such as International Atomic Energy Agency (IAEA) material tracking, etc.). When DOE owns facilities for its own purposes, it should fund or co-sponsor any non-proprietary R&D using these facilities to research or test models, instrumentation, controls approaches, etc. of possible application to current and future generations of NPPs.

DOE should support the initial regulatory approval costs under certain circumstances (sensor performance in harsh nuclear environments/incremental improvements needed by nuclear only). NE should sponsor NP-related research as a component of any DOE-wide initiatives in advanced simulation (e.g. IT^2), and provide access to its computational facilities and code-development capabilities comparable to the access provided to other energy technologies. DOE should establish and maintain ties to other agencies with similar advanced I&C needs (e.g., DOT, FAA, NRC, NASA, DOD, DOC, standards organizations). DOE should facilitate and fund cooperative R&D, domestic and foreign involving NRC, nuclear industry and advanced technologist (industry, university, laboratories). DOE should sponsor human-factors R&D and studies on populations drawing from the entire NP industry, and to promote human resource development at the interface between I&C/simulation technology and NPPs.

Appendix H

Working Group Report on – Advanced Nuclear Fuels/Fuel Cycles

Nuclear Energy Research Advisory Committee

Subcommittee for Long Term Planning for Nuclear Energy Research

Summary Report
Advanced Nuclear Fuel/Fuel Cycle Working Group
December 8-10, 1999 Workshop

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NERAC 2nd Strategic Planning Workshop, December, 1999

Advanced Nuclear Fuel Cycles Breakout Group Report

Introduction

The Advanced Nuclear Fuel Cycles Breakout Group (hereafter referred to as "the Group") discussed a wide range of fuels R&D needs associated with currently-installed commercial reactors ("generation 2" or "Gen 2"), the now available advanced light water reactors (Gen 3), some of which utilize Gen 2 fuel designs, and the reactors yet to be developed but anticipated to meet emerging power generation needs in the 21st century, and beyond (Gen 4). These issues and envisioned R&D activities were categorized into 6 research areas, which form the following 6 subsections of this report:

1. Higher-burnup Fuel for Gen-2 and Gen-3 Reactors
2. Gen 4 Fuels and Fuel Cycles
3. Fuel Operational Limit Phenomena
4. Th Fuel Cycle
5. Recycle/Reuse Technology
6. Enabling and Cross-Cutting Technologies

The issues and benefits that motivate the envisioned R&D in each of these areas were identified as were the challenges or barriers that would be addressed by R&D. Finally, specific research recommendations were developed for each identified research area, which included recommendations for subject matter as well as for approach. During the course of discussion, issues related to advanced nuclear fuel cycles and, more generally, nuclear energy R&D were discussed but determined to not be well classified within the six identified research areas. The essential substance of those discussions is reported in a separate subsection of this report, entitled Institutional Issues.

Higher-burnup Fuel

It was discussed that of the nation's 100-plus operating LWRs, as many as 90 would re-licensed for operation to about 2040. Therefore, improvements made to the current LWR fuel cycle in the next 10 to 20 years would have far-reaching impact. Group participants expressed that reactor-operating utilities are becoming increasingly interested in irradiating fuel beyond current burnup limits, which could have significant economic benefit. Therefore, higher-burnup fuel for current LWRs and potential advanced light water reactors is addressed specifically.

Drivers/Benefits:

Economics. The ability to irradiate fuel to higher burnup will enable plants to operate with longer cycle lengths (assuming that typical outage activities can be accommodated accordingly) and with more efficient fuel utilization.

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Proliferation Resistance. U.S. policy makers are increasingly interested in ensuring that nuclear fuel cycles are highly proliferation resistant. It is recognized that certain fresh- fuel compositions and longer in-reactor residence times (i.e., higher burnups) can each result in a spent fuel product that is unattractive for diversion to weapons.

Reliability. Operating costs are impacted by fuel failure rates; therefore, high reliability of fuel is important.

Safety. Although participants were careful to not imply that current reactor fuel designs are not safe, it was agreed that safety can be enhanced through improved fuel designs, which would facilitate licensing. It is noted that the NRC and EPRI are both engaged in a program to confirm the acceptability of the current peak rod burnup regulatory limit of 62 GWd/MTU, and possibly to provide a technical basis for increasing this limit.

Spent Fuel Disposal. Disposal of spent fuel from commercial reactors continues to be a concern to the public. It is agreed that higher-burnup fuels or fuel cycles could alleviate issues associated with spent fuel disposal by reducing the quantity of spent fuel to be disposed.

Spent Fuel Storage. Storage of spent fuel is a burden for operating utilities; therefore, reducing the amount of fuel to be stored prior to disposition would be beneficial.

Remove Incentive for Overseas Reprocessing. If new fuel designs offer improved economics and alleviate disposal issues, then incentives for reprocessing (i.e., separation of weapons-usable materials) can be reduced. This would further support U.S. non-proliferation policy.

Fuel Management Flexibility. Operational flexibility, including power upgrades, will likely be a key aspect of improving the economics of operating LWRs and advanced LWRs.

Challenges/Barriers:

Utility/industry. Acceptance of new fuel design that differ substantially from current designs will require in-pile verification of performance.

Regulatory. Implementation of significant changes to fuel design by licensees will require approval by the U.S. NRC, which requires that quality-assured analytic and experimental justification be provided. In addition, there are two generic limits, applicable to all vendors designs, which must be addressed: the 5% limit on U235 enrichment, and the 62 GWd/MTU on peak rod burnup.

Materials Performance Limitations. Fuel lifetime is currently limited by the degradation of cladding materials with increased exposure to reactor core environments. Advances with core and cladding materials will be required to realize higher-burnup potential.

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Insufficient Data. Currently, performance data at burnup values above 70 GWD/MTU (PWR basis) for existing fuel designs is limited. Development of higher-burnup fuel designs will require an understanding of the limitations of existing designs.

Lack of Irradiation Facilities. Development of new fuel designs will require irradiation of test fuel to burnup values above those currently being achieved. Such extended irradiation can be demonstrated in lead test assemblies operated in commercial reactors; however, if new fuel designs differ substantially from current designs, then government-owned test reactors are better suited to irradiate such fuel and assess fuel failure limits and post failure performance.

Enrichment Limitations (criticality and infrastructure limitations). The lack of criticality safety benchmark data for uranium enrichments greater than 5% U-235 (and less than 20%) makes difficult the licensing of commercial fuel facilities (throughout the fuel cycle chain) for higher enrichments. Also, the equipment in many facilities may not be capable of safely processing higher-enrichment uranium without modification.

Accommodation of Industrial Proprietary Interests. Although commercial proprietary interests can be accommodated in government-funded R&D programs, such accommodation must be considered from the outset of the program.

Implications for Handling, Storage, and Disposal of Spent Fuel. Fuel irradiated to higher burnup will have more fission products and minor actinides than current spent fuels (and, therefore, a higher decay heat loads and higher source term). Existing methods and licenses for managing spent fuel will need re-evaluation for higher-burnup fuel.

Predictive and Safety Analysis Capabilities. The techniques used currently for predicition of core behavior and for safety analysis will need to be evaluated for addressing use of higher-burnup fuel designs, and modified as appropriate.

Specific Research Recommendations

The Group proposes that NERAC recommend a joint government-industry program, similar in nature to the High Burnup Fuel Program of the 1980s. Such a program should include the following elements:

- The objective should be development of robust fuel designs capable of up to 100 GWD/MTU (batch average).

- The program should include hot cell examination of current fuel designs to enable an understanding of life-limiting phenomena, and to provide a foundation for increasing the burnup capability of existing designs.

- The program should include in-core performance assessment so that operating characteristics of higher-burnup fuel can be identified.

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- The program should include provision for obtaining criticality safety data for benchmarking of codes and methods to address enrichments above 5% and development of the regulatory infrastructure to support licensing of fuel at the increased enrichment.

- International participation should be sought, because the expected costs of a program would be sufficiently high that non-U.S. contributors (which would benefit from the results of the program) will be needed to share costs.

- International and university participation are desired to ensure that all potential innovations are considered for applicability and to aid in the development of new professionals through the universities.

- The program will require development of advanced fuel, cladding, and control materials if higher-burnup capability is to be attained.

- The program should build off of Advanced Materials and Fuels Technology program.
- The program should be complementary to the EPRI-NRC Robust Fuels Program.
- The Program can be considered a transition to more advanced Gen-4 concepts.

Gen-4 Fuels and Fuel Cycles

The Group agreed that the U.S. should embark upon a R&D program to develop a generation of reactors to be implemented in the next century. The Group further accepted the concept of a generation-4 (Gen-4) reactor concept as described by DOE-NE director, Bill Magwood, in several speeches and presentations. Because the general scope of R&D to address future reactor designs was being addressed by another breakout group, the Group pointedly considered only fuels and fuel cycles that might be used for such reactor designs. The discussion was intended to address fuel issues that would apply generally to any such reactor program, although it is acknowledged that issues associated with more exotic fuel concepts (e.g., liquid fuels) were not fully considered.

Drivers/Benefits:

Requirement for Anticipated Reactor Development. Regardless of the reactor technology (or technologies) to be pursued in any future reactor development program in the U.S., fuel and fuel cycle technology development will be a major component - both in the selection of the concept, and in its development.

Operational Safety (deployment considerations). It is believed that operational safety for the envisioned deployment of the reactor system(s) can be enhanced by development of a new fuel form and fuel cycle.

Enhanced Proliferation Resistance. Fuel technology will be a key component of a reactor system designed for enhanced proliferation resistance.

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Enhanced Resource Utilization. Fuel cycles developed for use with new reactor technologies are expected to allow more efficient utilization of fuel resources, through characteristics such as high-burnup capability, higher conversion ratio, etc.

High Reliability and Robustness. Simple and inexpensive operation of any new reactor designs will require low fuel failure rates (particularly for long lifetime, modular cores where fuel reconstitution and repair during an outage is not an option) and, perhaps, the ability to operate in a load-following mode.

Waste Minimization. Objectives for development of any new fuel cycle should include the minimization of waste.

Remove Incentive for New Fuel Handling Infrastructure at Deployment Sites. Depending on the reactor technology to be considered, a new design might obviate the need for fuel handling facilities at or near the reactor site. If such a system were deployed in a developing country, for example, then proliferation resistance is aided if that nation is not compelled to construct facilities to handle or process spent fuel.

Challenges/Barriers:

Materials Performance Limitations. Advances with core and cladding materials will be required if new reactor designs will utilize corrosive coolants (e.g., lead or lead-bismuth) or higher temperatures.

Gaining Access to Defense-Related Data and Performance Modeling. Participants in the group suggested that fuel development performed previously in the defense programs areas might be relevant to R&D for new reactor fuel systems. Gaining access to such information will be governed by National Security considerations, including energy security.

Lack of Appropriate Test Facilities. Development of fuel for new reactor concepts will require irradiation testing under prototypic conditions. For some systems now being proposed (e.g., lead-bismuth-cooled or gas-cooled reactors) prototypic test facilities do not exist in the U.S.

Integration to Emerging Reactor Development Program. Because development of new fuel cycles and new fuel forms consists of long lead-time activities, it is anticipated that some fuel development work would proceed in parallel with development of reactor concepts. It will be important that the fuel cycle development program is integrated with the reactor development program as it evolves.

Predictive and Safety Analysis Capabilities. New reactor and fuel concepts will require development of new models and analytical capabilities. The lack of such models (or the information with which to develop such models) will limit the extent of concept evaluation that can be performed using simulation tools.

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Enrichment Limitations (criticality and infrastructure limitations). The lack of criticality safety benchmark data for uranium enrichments greater than 5% U-235 (and less than 20%) makes difficult the licensing of commercial fuel facilities (throughout the fuel cycle chain) for higher enrichments. Also, the equipment in many facilities may not be capable of safely processing higher-enrichment uranium without modification. If higher-enrichment uranium is to be used for Gen-4 systems, then this issue must be addressed, as is the case for higher-burnup fuels for current reactors.

Question of Industrial Supply of Selected Materials. Innovative reactor designs may employ corrosive coolants or high coolant temperatures, requiring utilization of core and cladding materials not normally available commercially. Industrial supplies of such materials would need to be considered when planning R&D programs.

Specific Research Recommendations

The Group proposes that NERAC recommend research programs that consider the following:

- long-life cores (e.g., no refueling for 10+ years or cores that are designed for the duration of the plant life; Gen 2 and en 3 cores are addressed under Higher-burnup Fuel)
- robustness
- passive fuel and core response (i.e., benign consequences of fuel failure or benign fuel response to off-normal events)
- high-temperature fuel and materials performance
- incorporation of advanced information technology and "smart" technology into fuel management and fuel cycle concepts
- fuel-cycle front-end technologies (the front end of the fuel cycle was not addressed specifically in the proceedings; however, it was recognized that advances in technologies used to prepare fuel feed materials may well have beneficial impact on economics or waste management.)

Fuel Operational Limit Phenomena

Some Group participants advised that some operational limits placed on current plants are attributable to uncertainties in safety analyses. A particular example of this is the limits on channel power of PWRs imposed due to uncertainties in thermal hydraulic phenomena. Therefore, the Group proposes R&D to achieve better understanding of nuclear materials and fuel thermal and hydraulic phenomena that impact fuel operating limits and margins in Gen-2 and Gen-3 reactor systems.

Drivers/Benefits:

Improved Economics from Operational Flexibility. If limits can be made less restrictive, then plant operators can better optimize core loadings, thereby allowing better fuel utilization, and seek power upgrades.

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Reduction of Waste Associated with Fuel Usage. Better fuel utilization means fewer fuel assemblies used, which also means less fuel handling-associated waste.

Better-Defined Safety Margins. Reducing uncertainty in safety-related calculations will enable operators and regulators to know more precisely the safety margin for a given set of conditions.

Development of Better Analytical Tools. The key to reducing calculational uncertainties is incorporation of better models and better analytical tools - those models and tools would be available for other analytical needs.

International Interest in Topic. The international interest in an effort to address this concern provides an excellent opportunity for the U.S. DOE to collaborate with other nations.

Challenges/Barriers:

NRC Acceptance Uncertain. Clearly, any new approach to calculating safety margins would be successful only if the U.S. NRC accepts the new methods, which is currently uncertain. Therefore, some indication (and perhaps guidance) should be sought from the U.S. NRC.

Utilization Limited to Specific Applications. Although the models and techniques to be used to address these issues have broader applicability to LWRs, the applications are limited.

Complexity of Models Required. Modeling complex thermalhydraulic phenomena is not simple. Therefore, this will be a technically challenging problem.

Specific Research Recommendations

The Group proposes that NERAC recommend research programs that includes:

- thermal-hydraulics, materials, and nuclear phenomena (including post-failure phenomena) experimentation to benchmark existing models and to support the development of new models
- development of improved computational models

Th Fuel Cycle

The Group consensus was that the potential of Th fuel cycles should be re-considered. Some participants cited experience or research results that indicate that Th fuels may be attractive for intermediate-term and long-term application.

Drivers/Benefits:

Th/U-233 Fuel Cycle is Only Alternative to U/Pu. The U/Pu fuel cycle has been studied and developed extensively over the last several decades. However, the Th/U-233 fuel cycle has not been considered in similar detail, and it is the only long-term alternative to a U/Pu fuel cycle.

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Non-Proliferation. The radiation levels and chemistry associated with Th fuel cycles may effectively render Th-based fuel systems unattractive for diversion into weapons uses.

Potential Economic Benefit through Long-Term Conversion and Simplified Reactivity Management. The enhanced conversion that appears possible with Th-based fuels in thermal reactors may lead to extended burnup fuel designs. Simpler reactivity management schemes through a cycle would also be possible.

Chemical Stability of Form for Direct Disposal. The relative stability of ThO_2 (compared to that of UO_2) indicates that ThO_2 may be more durable in a repository.

Chemical Stability of Form for Operational and Safety Considerations. . The relative stability of ThO_2 (compared to that of UO_2) indicates that ThO_2 may be less reactive with reactor coolant (for example, during a failed-fuel event).

Resource Availability and Utilization. The reserves of Th are larger than reserves of uranium, indicating that Th can provide a long-term energy source.

Best (only) Alternative for Enhanced Conversion in LWRs (exclusive of recycle). A Th fuel cycle is the best identifiable alternative for incorporating enhanced conversion into LWR fuel cycles without fuel recycle.

Potentially Better Fuel Form for Gen-4. The attractive attributes of proposed Th fuel forms might be applicable to Gen-4 concepts as well as Gen-2 and Gen-3 reactors.

Effective for Enhanced Pu Consumption. Th-based fuels that incorporate separated Pu (or weapons Pu) would provide a means to reduce separated Pu inventories using the current base of reactors.

Challenges/Barriers:

Radiation Fields of Th-Based Fuels Impact Handling Requirements. The daughters and activation products of Th isotopes have significantly strong radiation fields, which may preclude fuel fabrication by conventional schemes.

Fabrication Difficulties. Fabrication of Th-based fuels may be more difficult than U-based fuels, and there is little experience with Th-based fuels.

Purity of Available Feed Materials. Because there is not currently a nuclear-related market for Th fuels, it is not clear that Th materials of the required purities will be available.

Less Operational Experience with Th Fuel Cycle.

No Infrastructure to Support Near-Term Implementation.

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No Clear Incentive for Conversion of Current Reactors to Th-Based Fuel Cycle. Although implementation of a Th-based fuel cycle might meet U.S. non-proliferation objectives, it is not clear that a sufficient economic incentive exists to entice current reactor operators to seek licenses for Th-based fuels.

Lack of Fundamental Data. There is little known data for Th fuels and for the physics of Th reactor cores. Improving that database would require significant experimental resources.

Specific Research Recommendations

The Group proposes that NERAC recommend an R&D program to investigate and develop Th fuel cycle technology. However, the program should address a fuel cycle to be used in a Gen-4 reactor system rather than current reactor systems; this suggestion is made because the Group consensus was that a radical change to the current fuel cycle in LWRs in the U.S. is not likely. The R&D program should include the following elements:

- determination of proliferation resistance strategy to set requirements
- measurement of nuclear data
- assessment of irradiation performance of fuel designs
- development of fuel fabrication processes
- fuel materials property characterization
- assessment of core performance and safety

Recycle/Reuse Technology (incl. Non-power uses)

- Non-aqueous Recycle (pyro, AIROX-like)

The Group proposes that technology R&D on recycle and re-use technology be resumed to offer options to future decision makers and to enable the U.S. to credibly influence how other nations might implement nuclear technology. Such technology will have potential to improve the economics, the resource utilization, and the proliferation resistance of the existing once through cycle. The specific technologies that should be considered are non-aqueous technologies such as pyroprocessing and other "dry recycle" technologies (i.e., similar to AIROX or DUPIC). Non-power uses of recycle options should be considered, and might include separation of key fission product isotopes for medical or industrial use.

Drivers/Benefits:

Improve Utilization of Fuel Resources. Any decision to implement recycle technology will necessarily be driven by economic considerations and a desire to improve utilization of resources.

Non-Proliferation Through Intrinsic Barriers. A key motivation for the U.S. to engage in recycle technology development might be the desire to offer to other nations alternatives to technologies that are not as proliferation resistant as the U.S. would prefer. Development of technologies that incorporate instrinsic barriers to proliferation or diversion may be possible.

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Utilization of a "Waste", Possibly for Non-Power Uses (i.e., supply of certain isotopes). Development of recycle technologies, or product-extraction technologies, will open the option of beneficial use of fission by-products.

Waste Management Improvements. Development of recycle technologies will increase the options available for waste management, perhaps reducing the quantity of waste to be disposed of and improving the economic viability of preferable nuclear energy technologies.

Opportunities for International Collaboration and Influence. Development and use of new recycle technologies, will enhance opportunity for international collaboration. Such collaboration enables the U.S. to influence development and selection of technologies for recycle overseas and to maintain technical understanding of technologies being developed in other nations.

Challenges/Barriers:

Clarification of Acceptability within National Non-Proliferation Policy. Successful initiation and implementation of a program to develop proliferation-resistant recycle technologies will clearly require clarification of the implications of U.S. non-proliferation policy.

U.S. Lags Behind Other Nations in Technology and Philosophy of Approach. The U.S. has not made important contributions to the international dialogue on acceptable recycle technologies for several years, and the U.S. has not been forced to consider the economic and waste management issues associated with recycle. Therefore, the U.S. may not be regarded as a serious contributor in this area until a substantial international collaboration is established.

Difficulty of Meeting Fuel Quality Requirements with Remote Processing and Fabrication Operations. There will be technical challenges to the preparation of acceptable-quality fuel from recycled materials.

Economics of Recycle and Re- Fabrication Techniques. Any new recycle technology developed in the U.S. must have the potential to reduce the overall fuel cycle costs for U.S. utilities, including the total cost of both the front end and the back end, including ultimate disposal.

Difficulty in Obtaining Irradiation Qualification Data in NRC-Regulated Facilities. Qualification of recycled fuel for use in existing reactors will require lead assembly irradiations in a licensed reactor.

Waste Management. New recycle technologies may produce new waste streams which must be considered in both the environmental and economic evaluation of the technologies benefits.

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Specific Research Recommendations

The Group proposes that NERAC recommend an R&D program to develop non-aqueous recycle technologies. The program should include the following elements:

- identification of preferred alternatives for development
- development of waste management technologies
- development of fuel processing and fabrication technologies
- assessment of recycled fuel performance
- development of separation techniques for desired isotopes as by-products
- international collaboration
- incorporation of advanced information technology and "smart technology" into fuel cycle and monitoring concepts

Enabling and Cross-CuttingTechnologies

The Group recognized that some research activities that may be proposed will benefit more than a single-mission program. Because most envisioned R&D programs are expected to be focused toward meeting relatively narrow program objectives, the R&D that often leads to technology advances that benefits many programs, but is sufficiently high-risk to be unattractive to a single-purpose program, may not have advocacy. Although the Group did not reach consensus as to the specific elements of such R&D, it is proposed that R&D be supported to make advances in the general technology area of the fuel cycle.

Drivers/Benefits:

Provision of Fundamental Data or Technology to Support Innovations in Initiative Areas. For example, the R&D envisioned might help researchers better understand fundamental corrosion processes in reactor core environments, which will then enable the development of corrosion-resistant cladding alloys.

Conduct of R&D That Can Lead to Advances and Innovations. R&D conducted outside the immediate needs of a schedule-driven program can often lead to advances that can subsequently be incorporated into a program. For example, the R&D envisioned might develop concepts for innovative cladding materials applicable to many fuel concepts under consideration

Means of Incorporating Universities. An R&D program of the type envisioned provides an excellent means of incorporating university research into relevant topics, without requiring that university personnel be part of a schedule-driven, focused program - conditions that might stifle creativity that can come from university R&D and inhibit the training of graduate students.

Effective Mechanism for International Collaboration. Although nations may not agree on a particular approach to reactor or fuel cycle technology, collaboration on a technology R&D program of the type envisioned can enable common ground for collaboration. Such R&D

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can also be conducted outside the realm of special technologies that nations may wish to keep proprietary.

Challenges/Barriers:

Available Facilities. Facilities for irradiation and post-irradiation examination of fuels and materials, particularly fast-spectrum facilities, are not conveniently available. Other facilities that are available are prohibitively expensive for smaller R&D efforts.

Instrumentation and Diagnostics. Development of new fuels and materials may require instruments and diagnostics that are yet to be developed.

Scaling and Experimental Techniques. Extrapolation of bench-scale R&D results to larger reactor systems will be a challenge, particularly if smaller and intermediate-size irradiation facilities are not available at reasonable cost.

Specific Research Recommendations

The Group proposes that NERAC recommend an Enabling and Cross-Cutting Technology R&D program for nuclear fuel cycle technology. Some suggested topics of research for this program include the following (although availability of resources would likely limit the scope of the program):

- research to understand fuel and materials degradation and failure mechanisms
- investigation of radiation-induced phenomena in fuels and materials
- research for enhanced understanding of physical phenomena and related modeling
- investigation of low-consequence failure phenomena (i.e., research into how fuel designs can be changed to make fuel response intrinsically benign after cladding breach.)
- research for in-reactor performance enhancement
- research to assess repository performance of disposed fuel and methods for enhancing repository performance
- research into advanced fuel fabrication techniques
- development of advanced absorber/control materials and techniques
- acquisition of additional nuclear data

Prioritization

The Group made only two comments regarding prioritization:

- Higher-burnup Fuels and Gen-4 Fuels and Fuel Cycles should be of highest and similar priority.
- Fuel Operational Limit Phenomena has prospect for near-term impact.

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Institutional Issues

In the course of discussion, several issues were raised that were applicable to many of the research topics being considered by the Group, or that were applicable to many aspects of technology being addressed in the Workshop. These are listed here, with some explanation.

Note: the Group did no+t specifically address fuel enrichment technology R&D, other than to propose it as a component of Gen-4-related research. The group notes that fuel enrichment costs are an important part of the cost of the uranium fuel cycle and might be considered further in another effort. Also, enrichment of desired isotopes in other core components may be beneficial if enrichment costs can be reduced.

User facilities should be made available to smaller R&D programs, which will enable a better incorporation of experimental research into R&D programs. The Group noted a disturbing trend away from experimentally-based R&D, toward more computer-oriented R&D, due to the difficulty in obtaining funding for experimental programs. In addition, irradiation facilities and post-irradiation examination capability are not readily available to researchers in universities or in institutions other than national laboratories.

The Group recommends that Information Technology and supercomputing capabilities be implemented in all R&D areas. Focused application and development of advanced computing techniques for modeling and simulation to resolve issues should be incorporated where appropriate. Furthermore, the Group believes that Incorporate Information Technology and "smart" sensors should be incorporated into fuel cycle and management concepts where appropriate - such incorporation will improve the transparency of fuel cycles (improving proliferation resistance) and will likely enable more efficient operation.

Better technology transfer across DOE organizations is needed. DOE, in defense and navy programs, has developed various technologies that may significantly improve commercial fuel economics, burnup, and safety. This information should be made available to the industry. The taxpayers paid for it. With the end of the cold war, this type of information can now be released.

Education, Infrastructure, and New Technology Application: the Group, in general, believed that a new vision and focus for future R&D is needed to attract the next generation of researchers. The Group also advocates incorporating student research into Laboratory and industry R&D programs as a means of providing interesting experiences for these students.

Waste fee considerations and implications for fuel cycle decisions should be considered. For example, does the current scheme of levying high-level waste fees on a per-MW-hr basis influence our R&D priorities and commercial fuel cycle decisions in a way that is counter to U.S. national interests?

A new paradigm for international partnership on fuel and fuel cycle development should be sought. This paradigm should include efforts to stay abreast of developments in foreign research initiatives.

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Participants

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Advanced Nuclear Fuel Cycles Breakout Group

Name	Organization	E-Mail Address
Marvin Fertel (Chair)	NEI	msf@nei.org
Paul Turinsky	NCSU	turinsky@eos.ncsu.edu
Tom Isaacs	LLNL	isaacs2@llnl.gov
Tom Sanders	SNL	tlsande@sandia.gov
Tom Coleman	FCF	thomas_a_coleman@framatech.com
Tom Rodack	ABB	tom.rodack@us.abb.com
Al Solomon	Purdue	solomon@ecn.purdue.edu
Allen Croff	ORNL	agc@ornl.gov
Norton Haberman	DOE-NE	norton.haberman@hq.doe.gov
Phil MacDonald	INEEL	pem@inel.gov
David Diamond	BNL	diamond@bnl.gov
John Sackett	ANL	john.sackett@anl.gov
Alan Waltar	Texas A&M	waltar@trinity.tamu.edu
Herbert Feinroth	Gamma Engineering	feinroth@bellatlantic.net
Charles Forsberg	ORNL	cwf@ornl.gov
Mujid Kazimi	MIT	kazimi@mit.edu
Vic Reis	SAIC	reisv@saic.com
Doug Crawford	ANL	douglas.crawford@anl.gov