TABLE OF CONTENTS

1. Introduction .................................................................................................................3
2. Program Overviews......................................................................................................3
3. Technology Developments Discussion........................................................................6
4. Potential Areas of Collaboration and Future Meetings................................................8
5. Facilities Visits and Campus Tours..............................................................................8

Attachments

1. Agenda
2. List of Participants
3. Group Photograph
1. INTRODUCTION

Despite its relatively low concentration (~3 parts per billion in seawater), the tremendous amount of uranium dissolved in the sea (more than 4,000 million tonnes) has long been regarded as a nearly inexhaustible resource. Many government-sponsored research and development (R&D) activities were carried out in the 1970s and 1980s. However, most of the studies were subsequently suspended due to low recovery efficiency and modest uranium market prices. Japan is one of the few nations that has persisted in seawater extraction and maintained by far the largest research efforts.

Extraction of uranium from seawater was identified as a new collaboration activity for the Fuel Cycle Technology Working Group (FCTWG) during the U.S.-Japan Nuclear Energy Action Plan Steering Committee meeting held on March 19, 2010. The co-chairs of FCTWG, Drs. Hide Funasaka and Jim Laidler, agreed to include this topic in the future cooperation scopes. Subsequently, Dr. Stephen Kung and Dr. Masao Tamada were appointed to serve as points of contact to facilitate the development of the collaboration.

After several months’ planning, the first uranium extraction from seawater information exchange meeting was held at Lawrence Berkeley National Laboratory on June 24-25, 2010. The purpose of this meeting was to provide an initial face-to-face technical discussion opportunity and to review current technology developments status and program activities from each country. The meeting followed the agenda shown in Attachment 1.

2. PROGRAM OVERVIEWS

Dr. Stephen Kung opened the meeting with introductions and welcoming remarks. All meeting participants introduced themselves, their affiliation, and particular areas of expertise. Participants in attendance at the meeting are listed in Attachment 2. The proposed meeting agenda was approved as the framework of the meeting, while both sides also agreed to adopt a discussion format that allowed all presentations to be interspersed with questions and detailed explanations.

U.S. Fuel Resources Program

The U.S. R&D efforts in seawater uranium extraction have been dormant for more than two decades. Currently, the Fuel Cycle R&D program in the Office of Nuclear Energy
plans to explore and exploit recent developments in high performance computing, nanoscience and nanomanufacturing technologies that could offer promising new directions that may enable technical breakthroughs. The program’s goal is to enhance energy security by assuring that sustainable and economically viable supplies of nuclear fuel materials will be available.

The program activities in fuel resources will include resource estimation, exploration and extraction. For resource extraction, the program seeks to evaluate uranium resources and develop recovery technologies to increase its availability to enable sustainable fuel cycles. The details for resource estimation and exploration have not been defined at this time. The program plans to identify potential opportunities through future technical workshops and in consultation with U.S. Geological Survey, Energy Information Administration, Nuclear Energy Agency and International Atomic Energy Agency.

For resource extraction, the emphasis is to identify and implement high risk, high pay-off R&D to ensure long-term resource availability. The R&D activities will focus on uranium recovery technologies that are not currently being pursued by private industry or non-governmental organizations. It’s appropriate and critical for federal involvement to support long-term, game-changing approaches such as recovery of uranium from seawater.

The currently planned R&D activities include: establishing a baseline of cost analysis, methodology, and uncertainties of the technology; synthesizing novel nanoscale materials with tailored architectures for specific chemical performance; characterizing materials and dynamic chemical processes at the atomic and molecular level; and simulating and predicting structural and functional relationships using modern computational tools, including high performance computing.

**Japan Seawater Uranium Extraction Technology Development Status**

Dr. Masao Tamada presented an overview of the current status of uranium collection from seawater using adsorbents grafted on polymers through radiation processing. Dr. Tamada introduced the Takasaki site and other JAEA facilities in Japan. Dr. Tamada is the Unit Manager of the Environment and Industrial Materials Research (EIMR) Division at Quantum Beam Science Directorate (QuBS).

There are three major irradiation facilities: a gamma-ray facility (in operation since 1964 with a Co-60 source), an electron beam irradiation facility (in renewal in 1978), and an ion accelerator facility (in operation since 1993) at Takasaki Advanced Radiation Research Institute (TARI). The Environmental Polymer Group (EP), consisting of four researchers, in EIMR division developed the high performance adsorbent with radiation processing technology for industrial applications such as removal of toxic metal ion and collection of rare metals. EP has prepared the fibrous
adsorbent for uranium extraction from seawater and carried out the marine experiment to evaluate the uranium collection from seawater.

Uranium adsorbent materials were prepared by radiation processing of polymers. During the process, the polymer is first irradiated to create active sites, followed by incorporation of desired functional groups onto the trunk materials. The technologies of polymer modified by radiation process have been widely adopted for industrial applications such as separator membrane in button-shaped battery and air filter for clean room.

Uranium, as a conventional mineral resource, is considered at the borderline of being cost effective. The development of uranium adsorbent research started in the middle of 1960s. In 1973, the Japanese government sponsored an experimental plant for uranium collection from seawater using titanium oxide. The prohibitively high pumping costs plus the low mechanical strength of the hydrous titanium oxide absorbent led the researchers to pursue investigation of the graft polymerization with amidoxime type of functional groups. The synthesis of fabric adsorbent and their applications and characteristics were subsequently developed at EP.

In 1999, a new 3-year effort was initiated to start the marine experiments of the mass-produced adsorbent fabric materials. A stack design with a floating frame and cage of adsorption beds was placed about 7-kilometer offshore near Aomori, Japan. The adsorption beds, containing ~350 kg of adsorbent materials in maximum, were suspended on a floating frame down at least 20-meter from the surface. A crane ship was used for hanging the cage of adsorption beds from the floating frame every 20-40 days. A total of 1 kg of uranium was collected as yellow cake. Dilute acid (0.5M HCl) was used to elute the sorbed uranium from the adsorbent materials. A follow-up purification by solvent extraction provided the final uranium feed for yellow cake production.

The costs associated with the floating frame and cage in the stack design represented ~80% of the collection cost. A new collection system for cost reduction by using a braid type adsorbent was developed later in the marine testing. In this braid design, polyethylene fiber was treated by radiation process to generate the braided adsorbent materials. The 60-meter long adsorbent was evaluated in Okinawa, Japan. The braid adsorbent was moored to the sea floor with a remote control device and stood/floated in the sea currents.

In this new design, the recovery of uranium using the braid absorbent system was 1.5 g U/kg-ad versus 0.5 g U/kg-ad with the stack methods, due to the higher efficiency of the braid system than the stack system as well as a 10°C temperature increase. The estimated uranium yellow cake has been recovery cost was 25,000 yen/kg for a 1,200 t plant design with an adsorbent lifetime of 18 adsorption/elution cycles.
Reducing adsorbent production cost and increasing repetition usage of the adsorbent will reduce the technology cost. Further studies are necessary to modify the performance of uranium adsorbents. As compared with other electric generation methods in Japan, nuclear electricity falls between 4.8 - 7.7 cents/kWh. So far, nuclear power generation is still lower in cost than solar (42.7 cent/kWh), wind (10.5 cent/kWh), hydraulic (10.9 cent/kWh) and other renewable power generation methods.

Recent publications on uranium absorption from seawater indicated that India, France, and Japan have continued research efforts on various adsorbent types, i.e. biosorption, chitosan resins, hydrogels, and amidoximated membranes. Future work will concentrate on increasing repetitions of adsorbent loading and elution and looking into the co-collection of other metals of value.

3. TECHNOLOGY DEVELOPMENTS DISCUSSION

Cost/Economic Analysis

Dr. Erich Schneider from the University of Texas at Austin led the discussion in the area of recovery cost analysis and methodology. It appears that additional information is available in more recent publications; however, not all cost estimates publications are available in English. Dr. Tamada indicated that he may be able to share some recent cost analysis information and provided a contact person for Erich to follow up.

The participants exchanged viewpoints on cost analysis and methodology, especially focusing on understanding the uncertainties. For example, environmental analysis or regulatory costs should be considered, at least in the U.S. analysis. The cost of interest on the capital outlay may also represent a large effect on the recovery cost of the uranium, from $200/kg at 3% interest to $300/kg at 10% interest.

The need for an energy balance on the cost of recovery versus the value of energy gained from the material was discussed. Other factors that must be evaluated in the cost analysis, including the optimization of the number of loading/elution cycles, the degradation of the absorbent, the mapping of the potential ocean areas for optimum recovery, the most efficient current velocity for maximum loading/recovery, and the side benefits of recovering additional elements.

Preparation of Sorbent Materials

Chris Janke of Oak Ridge National Laboratory led the discussion on novel synthesis and characterization of advanced adsorbent materials. The discussion focused on the
polymers selection, characteristics, and the effects of irradiation conditions on radical formation and stability.

High density polyethylene-based sorbent materials were chosen for their high uranium adsorption properties, mechanical stability and commercial availability in the desired textile forms for functional group grafting. Nonwoven materials were irradiated with electron beams at room temperature while braidable fiber spools were irradiated with gamma rays at -78°C. Uranium adsorption was demonstrated to increase as the fiber surface area increased. The weight ratio of the adsorbent material to the monomers does not appear to be an issue since the monomer concentration is present in excess.

However, the dissolution of the polymer in the grafting solution does result in higher viscosity and final discard of the solution as waste. These concentrations and solution recycle need to be optimized since the cost of the monomer is a significant portion of the cost of the adsorbent. Additional functional groups may show promise in preliminary testing but the grafting of these functional groups can change the selectivity or loading due to the functional group arrangement on the grafted material.

### Coordination Chemistry and Ligands Design

Dr. Linfeng Rao of Lawrence Berkeley National Laboratory led the discussion on uranium retention mechanism and kinetics, and on the use of computational tools for uranium coordination chemistry and ligand design. The uranium chemistry in seawater and the complexation of the uranyl ion by the promising functional groups were covered. It is well known that both the oxygen and nitrogen atoms become electron donors for transition metals. However, there are ligands that are interacting stronger and/or more selective for uranyl. Other factors (cost, stability, and durability) should also be considered for practical adsorbents.

The ideal functional ligand group would be robust, inexpensive, and easy to manufacture on a large scale; provide strong binding and selectivity for uranium; and be fast and easy to elute. The functional group needs to be easily grafted onto the polymer support for deployment in a marine environment. The elution of the uranium in other solutions was discussed and possible improvement may be realized with carbonate elution.

The sorption reactions were discussed since improved adsorption was observed with the addition of acidic ligands. The idea of using a charged ligand to enhance the adsorption of the anion complex could give some improvement, but effectiveness of such ligands at the high ionic strength in seawater is uncertain. Uranium absorption appears to be 1.5 times higher with a temperature increase from 20 to 30°C. The enhancement at higher temperatures appears to be a kinetic effect rather than an equilibrium effect.
Resource Estimation by Geo-neutrinos

Dr. Steve Herring of Idaho National Laboratory presented the fundamental measures of uranium resources. The presentation discussed the initial source of all the elements heavier than nickel and the explosion of supernovae. The estimated global uranium inventory, as indicated by geo-neutrino data, generally agrees with the astrophysical models for uranium nucleo-synthesis and geological estimates. Both the geological and geo-neutrino data conclude that most of the uranium should be in the continental crust, but the data cannot predict the location of the resources or the difficulty of extraction.

4. AREAS OF COLLABORATION AND FUTURE MEETINGS

U.S. program will focus on the extraction of uranium from seawater. In this area, the formulation of cost estimates for the recovery of uranium from seawater is identified as an area for near term collaboration. This collaboration will allow both parties to derive an updated estimation of the cost for the recovery of this valuable resource. Dr. Schneider is appointed as the point of contact for leading the cost estimation from the U.S. side. Dr. Tamada will appoint a contact person from the Japan side. The goal is to conduct a validation of the current estimates, to understand the underlying assumptions, and to define areas where additional inputs are needed.

Pending on future funding situation from both sides, additional collaboration topics will be developed in future information exchange meetings. The group proposes to hold the next seawater uranium extraction information exchange meeting in Japan in 2011. Meanwhile, informal communications or visits between the participants are encouraged.

5. USER FACILITIES AND CAMPUS TOURS

After the meeting adjourned on Friday, the group toured two scientific DOE user facilities located at Lawrence Berkeley National Laboratory – the Molecular Foundry and the Advanced Light Source. On Friday afternoon, the group also toured the University of California-Berkeley Campus.
Attachments 1: Meeting Agenda

Information Exchange Meeting on Uranium Extraction from Seawater
Fuel Cycle Technology Working Group
June 24-25, 2010

Building 54, Room 130B
Lawrence Berkeley National Laboratory
Berkeley, California USA

Wednesday, June 23
Dr. Tamada arrives in USA (San Francisco airport) and stays at Doubletree Hotel & Executive Meeting Center@ 200 Marina Blvd., Berkeley, California.

Thursday, June 24
8:30 am – 11:30 am
Welcome
Introduction of Participants
Review of Agenda
U.S. Fuel Resources Program Overview
Japan Program on Seawater U Technology Development
RD&D status and current activities/emphasis
11:30 am – 12:30 pm Lunch at LBNL Café
12:30 pm – 5:30 pm
Discussion on Technology Developments
U chemistry
Sorbent materials
Cost analyses
Marine deployment
6:00 pm No Host Group Dinner

Friday, June 25
8:00 am – 12:30 pm
Continue discussion on technology developments
12:30 pm – 1:30 pm Lunch at LBNL Café
1:30 pm – 4:30 pm
Discussion on potential collaboration area(s)
Preparing meeting records and future information exchange dates and logistics
Tours of LBNL Facilities
Advanced Light Source
Molecular Foundry

Saturday, June 26
Dr. Tamada Departs SF
## Attachments 2: List of Meeting Participants

**JAPAN:**

Masao Tamada  
JAEA  
tamada.masao@jaea.go.jp  
81273469213

**UNITED STATES:**

Stephen Kung  
DOE  
Stephen.kung@hq.doe.gov  
301-903-8074

Chris Janke  
ORNL  
Jnk@ornl.gov  
865-574-9247

Kevin Felker  
ORNL  
Felkerlk@ornl.gov  
865-576-8213

Stephen Herring  
INL  
J.herring@inl.gov  
208-526-9497

Erich Schneider  
UT/Austin  
ESchneider@mail.utexas.edu  
512-592-1374

Linfeng Rao  
LBNL  
LRao@lbl.gov  
510-486-5427

Guoxin Tian  
LBNL  
Gtian@lbl.gov  
510-486-5141
Attachments 3: Group Photograph of Participants

Photo from Left to Right: