Summary of the
U.S. DOE Informational Meeting on Nuclear Fuel Cycle Evaluation Metrics
Argonne National Laboratory
November 8-9, 2012

Background and Objectives

As part of activities leading to a comprehensive evaluation and screening of nuclear fuel cycle options in 2013, the United States Department of Energy (U.S. DOE) Office of Fuel Cycle Technologies held an *Informational Meeting on Nuclear Fuel Cycle Evaluation Metrics* at the Argonne National Laboratory, Argonne, IL, November 8-9, 2012.

The meeting was attended by about 50 participants largely from universities, industry and DOE national laboratories.

The objectives of this informational meeting were:

- Describe the purpose and objectives of the 2013 Evaluation and Screening of Fuel Cycle Options being conducted for the DOE Office of Fuel Cycle Technologies,
- Discuss the nuclear fuel cycle evaluation metrics and the methodologies for evaluating them that have been developed within the USDOE FCT program office,
- Obtain feedback on the metrics from the meeting participants.

The purpose of the Evaluation and Screening effort is to develop information on the potential benefits and challenges of nuclear fuel cycle options (i.e., the complete nuclear energy system from mining to disposal) that can be used to strengthen the basis and provide guidance for the prioritization of research & development activities undertaken by the Office of Fuel Cycle Technologies. Nine evaluation criteria have been designated by the DOE Office of Nuclear Energy for the evaluation and screening: Nuclear Waste Management; Proliferation Risk; Nuclear Material Security Risk; Safety; Financial Risk and Economics; Environmental Impact; Resource Utilization; Development and Deployment Risk; and Institutional Issues. In order to apply these criteria for the evaluation and screening of a comprehensive set of fuel cycle options, draft evaluation *metrics*, including definitions and methodologies for evaluating them, have been developed. These metrics are intended to provide insights on advanced fuel cycle approaches that have the potential for achieving substantial improvements with respect to the nine criteria in comparison to the current nuclear fuel cycle in the United States.

During the meeting, draft metrics and their evaluation methodologies were presented to obtain feedback from meeting participants on the:

(1) adequacy of the metrics for informing on each of the nine high-level evaluation criteria, and

(2) appropriateness of the methodologies for metric evaluations including the assumptions being made.

Meeting Proceedings

To accomplish the meeting objectives, the meeting covered the following topics in the Plenary Sessions:

- Purpose and Objectives of the 2013 Evaluation and Screening Effort
- Introduction to Draft Evaluation Metrics.

For effective engagement of the meeting participants, discussions were organized into two Break-out Sessions in addition to the Plenary Sessions. Each Break-out Session consisted of three separate groups, each devoted to discussing three of the nine evaluation criteria and associated metrics (see Table I). Each Group had two co-Chairs facilitating the discussions and ensuring engagement of all participants, and one scribe to capture the salient points of the discussion. One co-Chair was a member of the Evaluation and Screening Team (EST), the team responsible for the 2013 Evaluation and Screening (E&S). The other co-Chair was from the nuclear industry (see Table I).

Table I. Break-out Groups and co-Chairs

Break-out Group	**Co-Chairs**
Criteria Set 1 (*Safety; Proliferation Risk; Nuclear Material Security Risk*)	R. Jubin (ORNL) & A. Sowder (EPRI)
Criteria Set 2 (*Nuclear Waste Management; Environmental Impact; Resource Utilization*)	W. Halsey (LLNL) & C. Phillips (ES)
Criteria Set 3 (*Financial Risk & Economics; Development & Deployment Risk; Institutional Issues*)	J. Gehin (ORNL) & P. Murray (AREVA)

The Agenda for the meeting is provided in Attachment A.

A complete list of the draft evaluation metrics discussed during the meeting is provided as Attachment B. Attachment C contains a summary of the feedback obtained from the three Break-out Groups. The presentation materials used during the Plenary Sessions of the meeting can be obtained from http://www.inl.gov/conferences/nfcemm/presentations.shtml .

The list of participants at the meeting is presented in Attachment D.

Conclusions

The U.S. DOE Informational Meeting on Nuclear Fuel Cycle Evaluation Metrics, held November 8-9, 2013, successfully communicated information on the effort to develop evaluation metrics for a planned Evaluation & Screening of Fuel Cycle Options, and provided an opportunity for participants to give feedback on the draft metrics. Briefings were given on the purpose and objectives of the 2013 Evaluation and Screening activity and draft metrics that have been developed by an Evaluation and Screening Team established by the U.S. DOE. The meeting resulted in valuable insights and feedback on metrics that will be considered as part of the 2013 Evaluation and Screening effort.

Attachment A

U.S. DOE Informational Meeting on Nuclear Fuel Cycle Evaluation Metrics
Argonne National Laboratory
November 8-9, 2012

AGENDA

Thursday, November 8, 2012

Time	Subject	Lead
	Plenary Session: Introductory Presentations Bldg. 208, A-138	
8:00 – 8:05 am	Welcome Address	T. Taiwo (ANL)
8:05 – 8:15 am	Opening Remarks	B. P. Singh (DOE-NE)
8:15 – 9:00 am	Purpose and Objectives of the 2013 Evaluation and Screening Effort *(Background, Context, Overall Process, Introduction of Nine Evaluation Criteria)*	T. Taiwo (ANL)
9:00 – 10:15 am	Introduction to Draft Evaluation Metrics	W. Halsey (LLNL)
10:15 – 10:30 am	Instructions on Break-out Session I (*including assignments to Break-out groups*)	K. Jenni (Insight Decisions)
10:30 – 10:45 am	**Break – Reconvene in Breakout Session rooms**	
10:45 – 3:00 pm	**Break-out Session I: Deliberations on Metrics (Rooms C-234, A-138, and L-110)**	
	Criteria Set 1 – Bldg. 208, Room Option 1	R. Jubin (ORNL) & A. Sowder (EPRI)
	Criteria Set 2 – Bldg. 208, Room Option 2	W. Halsey (LLNL) & C. Phillips (ES)
	Criteria Set 3 – Bldg. 208, Room Option 3	J. Gehin (ORNL) & P. Murray (AREVA)
11:45 – 1:00 pm	**Lunch (on your own** – *A good option is the Argonne Cafeteria, Bldg. 213***)**	
3:00 – 3:15 pm	**Break – Reconvene in Room A-138**	
	Plenary Session: Preliminary Feedback from Break-out Sessions; Bldg. 208, A-138	
3:15 – 3:55 pm	**Criteria Set 1** (*Safety; Proliferation Risk; Nuclear Material Security Risk*)	R. Jubin (ORNL) & A. Sowder (EPRI)
3:55 – 4:35 pm	**Criteria Set 2** (*Nuclear Waste Management; Environmental Impact; Resource Utilization*)	W. Halsey (LLNL) & C. Phillips (ES)
4:35 – 5:15 pm	**Criteria Set 3** (*Financial Risk & Economics; Development & Deployment Risk; Institutional Issues*)	J. Gehin (ORNL) & P. Murray (AREVA)
5:15 – 5:30 pm	Application Methodology Issues	W. Halsey (LLNL)
5:30 – 5:40 pm	Instructions for Break-out Session II	T. Taiwo (ANL)
5:40 pm	**Adjourn**	

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AGENDA

Friday, November 9, 2012

Time	Subject	Lead
8:00 – 10:00 am	**Break-out Session II: Methodology and Finalization of Feedback on Metrics (Rooms C-234, A-138, and L-110)**	
	Criteria Set 1 – Bldg. 208, Room Option 1	R. Jubin (ORNL) & A. Sowder (EPRI)
	Criteria Set 2 – Bldg. 208, Room Option 2	W. Halsey (LLNL) & C. Phillips (ES)
	Criteria Set 3 – Bldg. 208, Room Option 3	J. Gehin (ORNL) & P. Murray (AREVA)
10:00 – 10:15 am	**Break – Reconvene in Room A-138**	
	Plenary Session: Final Feedback from Break-out Sessions Bldg. 208, A-138	
10:15 – 11:00 am	Feedback on Metrics for **Criteria Set 1**	R. Jubin (ORNL) & A. Sowder (EPRI)
11:00 – 11:45 am	Feedback on Metrics for **Criteria Set 2**	W. Halsey (LLNL) & C. Phillips (ES)
11:45 – 12:30 pm	Feedback on Metrics for **Criteria Set 3**	J. Gehin (ORNL) & P. Murray (AREVA)
12:30 – 12:45 pm	**End of Meeting on Evaluation Metrics**	T. Taiwo (ANL)
	Meeting on Finalization of Feedback on Metrics (Limited Participation, Break-out Session Leads Only) Bldg. 208, Rm A-138	
2:00 – 5:30 pm	Finalization of Feedback on Metrics	W. Halsey, T. Taiwo, J. Gehin, K. Jenni, R. Jubin, A. Sowder, etc.
5:30 pm	**Adjourn**	

Attachment B

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EVALUATION CRITERIA AND DRAFT METRICS

Proliferation Risk (Group 1*)

- Maximum FOM_1 (nominal fuel cycle material)
- Maximum FOM_1 (material with misuse of technology included in the fuel cycle)
- Maximum FOM_1 (material with clandestine use of any technology)

Nuclear Material Security Risk (Group 1)

- Maximum FOM_1 (nominal fuel cycle material)

Safety (Group 1)

- Relative Safety Management Challenge for all facilities and processes

Nuclear Waste Management (Group 2)

- Mass of SNF+HLW disposed per energy generated *(t/GWe-yr)*
- Activity of SNF+HLW (100 years) per energy generated *(MCi/GWe-yr)*
- Activity of SNF+HLW (100,000 years) per energy generated *(MCi/GWe-yr)*
- Mass of DU/RU disposed per energy generated *(t/GWe-yr)*
- Volume of LLW per energy generated *(m^3/GWe-yr)*

Environmental Impact (Group 2)

- Land Use per unit of energy production *(km^2/GWe-yr)*
- Water Use per unit of energy production *(ML//GWe-yr)*
- Radiological impact - total estimated worker dose per unit of energy production (Person-mSv/GWe-yr)
- Chemical impact - chemical hazard index per unit of energy production *(Hazard Index(HI)/GWe-yr)*
- Carbon impact - CO_2 released per unit of energy production *(Mt/GWe-yr)*

Resource Utilization (Group 2)

- Natural uranium required per unit of energy production (*t/GWe-yr)*
- Natural thorium required per unit of energy production (*t/GWe-yr)*

Financial Risk and Economics (Group 3)

- Levelized Cost of Electricity at Equilibrium (LCAE)

Development and Deployment Risk (Group 3)

- Development time
- Development cost
- Compatibility with the existing infrastructure
- Existence of NRC regulations for the fuel cycle and familiarity with licensing

Institutional Issues (Group 3)

- Compatibility with the existing infrastructure
- Existence of NRC regulations for the fuel cycle and familiarity with licensing

*Group number indicates the Break-out Group under which the criterion and associated metric(s) were discussed.

Attachment C

U.S. DOE Informational Meeting on Nuclear Fuel Cycle Evaluation Metrics
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Summary of Feedback from Break-out Groups

SUMMARY OF DISCUSSION, BREAK-OUT GROUP 1

Criteria:

- Proliferation Risk
- Nuclear Material Security Risk
- Safety.

Participants:

First Name	Last Name	Company
Sven	BADER	AREVA
Sunil	CHIRAYATH	Texas A&M University
Allen	CROFF	Vanderbilt University
Scott	DEMUTH	Los Alamos National Laboratory
Felicia A.	DURÁN	Sandia National Laboratories
Edward	HOFFMAN	Argonne National Laboratory
Robert	JUBIN	Oak Ridge National Laboratory (co-Chair)
Michael	MILLER	Los Alamos National Laboratory
Linda	NOZICK	US Nuclear Waste Technical Review Board
Andrew	SOWDER	Electric Power Research Institute (co-Chair)
Andrew	WORRALL	Oak Ridge National Laboratory (Scribe)

Proliferation Risk

Draft Criterion Definition: The risk of a nation ("host-state") using civilian nuclear activities (such as materials, facilities, or technologies) to obtain materials usable in nuclear weapons.

Draft Metrics:

- Maximum FOM_1 (nominal fuel cycle material)
- Maximum FOM_1 (material with misuse of technology included in the fuel cycle)
- Maximum FOM_1 (material with clandestine use of any technology).

Discussion:

No new metrics or changes were proposed to the existing metrics.

The participants agreed that the use of FOM_1 was appropriate for the "risk" element of evaluating the proliferation concerns of fuel cycles. However, the general consensus of the group was that FOM_1 does not provide the full picture of the proliferation "resistance" of the fuel cycle and that this needed to be made clearer upfront. Once explained by the representatives of the Evaluation and Screening Team (EST), it was agreed that a subsequent, more detailed assessment would be necessary to provide a complete picture of the proliferation risk, taking into account the additional issues such as number of barriers (time, cost, institutional etc.), but that this was not appropriate for the current Evaluation and Screening as this would be more technology specific. The fact that FOM_1 calculations would use publicly available material was received positively by the group and it was agreed that this makes FOM_1 the most appropriate metric at this time.

Addressing the "safeguardability" of the fuel cycle technology was considered necessary in follow-on evaluations.

There was also concern raised by the group that FOM_1 did not take into account the material form i.e., liquid, fine powder etc., required to actually convert the material into something usable as a weapon. It was suggested that the EST should consider the material form as they step through the fuel cycle assessment and that this consideration is also relevant to the material security and use in a radioactive dispersal device (RDD - see discussion under Nuclear Material Security Risk below).

The group noted that different fuel cycle options (or maybe technologies) could show the same FOM_1 score, but that this might not indicate how easy it is to separate/purify materials further and consequently raise the FOM_1 score from medium to high. For example, plutonium (Pu) in powder form versus Pu in MOX fuel might have the same FOM_1, but it could be much easier to separate the pure material. This discussion also highlights whether the assessments at the fuel cycle level would require knowledge and assumptions about the technology e.g., PUREX versus COEX and assumptions in the split in the COEX extraction.

The group recommended that the purpose and difference in the three FOM_1 applications needed clarification by the EST as it is not transparent at first read, in particular for the 2nd and 3rd FOM_1 metrics.

The participants agreed that the methodology for the FOM_1 metric is appropriate and no changes were proposed. However, the following issues raised by the group suggest that further clarification of them by the EST might be necessary:

- The group wondered how the "sensitive" points in the fuel cycle will be identified and captured without completing an explicit FOM_1 calculation for all stages in that fuel cycle. The EST representatives explained that this would be done using expert judgment. Concern was also raised at the level of effort that would be required to do

this for all of the steps. The group also felt it is important to consider how long the fuel material might be in a given sensitive point. However, an EST representative noted that this is more of a safeguarding issue which was excluded from this metric.

- The group also noted that using only the maximum FOM_1 score in the fuel cycle would not differentiate between a fuel cycle that had only 1 "high" FOM_1 score (stage) and another that had 10 "high" FOM_1 stages. It <u>was suggested by the group that counting the number of "high" stages or providing the range of FOM_1 scores in the fuel cycle could be of benefit</u>.
- The use of bins for grouping the scores was agreed to be appropriate, as long as these bins were consistent with the existing definitions. e.g., Bathke, DOE etc. Several members of the group noted that there is new R&D underway in the FOM_1 and proliferation resistance concepts in the United States (and internationally) that is likely to change the way these assessments are done and the EST needs to be at least cognizant of these developments and to the extent possible may want to revise the methodology accordingly if deemed necessary.
- In terms of the weighting (i.e., assigning relative importance of the metrics within this criterion), since the 3rd of the FOM_1 values is not a major differentiator as all fuel cycles are equal, should it not carry less weight? Or is the 3rd the most important since this is where most of the historic proliferation risk has occurred? <u>The group agreed that this would depend on the assessor's viewpoint and so in the absence of other information, an equal weighting is appropriate</u>.
- The 3rd FOM_1 was initially questioned on the basis that it seemed to capture all fuel cycle options and therefore did not provide any discrimination among options. However, this feature was subsequently seen as a strength in that its broadness ensured that, for the purposes of screening, even those fuel cycles that did not require either enrichment or reprocessing/separations but did involve elements of concern, such as the use of heavy water, would be captured. The lack of discrimination by this metric also reflects a general observation by many experts that proliferation risk is not a good discriminator at the fuel cycle level.

Nuclear Material Security Risk

Draft Criterion Definition: The risk of nuclear materials being diverted from civilian nuclear activities by "sub-national" or terrorist groups for use in nuclear weapons or radioactive dispersal devices (RDD).

Draft Metric:

- Maximum FOM_1 (nominal fuel cycle material).

Discussion:

<u>The group concluded that the current metric (FOM_1) does not address the potential use of nuclear material in a Radiological Dispersion Device (RDD), but only as an Improvised Nuclear Device (IND). It suggested that a second metric should be developed to account for the security risk of material use in an RDD.</u>

The group discussed potential metrics for the RDD issue raised above. Evaluation of the materials present in each stage of the fuel cycle as "worse than", "better than", "the same" relative to the reference (existing) fuel cycle is recommended since, for example, an explicit calculation of specific radioactivity is difficult and inappropriate at this time. Other better, more detailed metrics (such as specific or total radioactivity) may be appropriate at the technology level of assessment. This could be completed at the same time the EST evaluates the FOM_1 score as this would save time and ensure consistency.

In terms of combining the metrics, the group indicated that FOM_1 alone is insufficient to provide an assessment of RDD potential. It was therefore recommended that FOM_1 should be binned similarly to the RDD metric discussed above such that it could be more easily combined with a newly developed RDD metric. A simple relative ranking scheme consisting of three bins was recommended at this stage for each of the two metrics, i.e., Middle bin "same" as reference fuel cycle, a bin for "worse" than reference fuel cycle (e.g. when separations are part of the fuel cycle), and a bin for "better" than the reference fuel cycle. A second three-bin structure for FOM_1 was also discussed in which the top bin would reflect those fuel cycles that had FOM_1 value > 2 (i.e., preferred weapons material at only sensitive point); the second bin would correspond to a FOM_1 value between 1 and 2 at any point; and the third bin would be for a FOM_1 value < 1, i.e., unattractive material. The group was unable to determine a way forward on the weighting in the time available due to the vastly different risk profiles represented by the two threats (IND vs. RDD). It was recommended that the weighting of the metrics be considered as part of a sensitivity analysis.

Safety

Draft Criterion Definition: The challenge of assuring the safe implementation of nuclear energy and compliance with existing and future safety requirements.

Draft Metric:

- Relative Safety Management Challenge for all facilities and processes.

Discussion:

<u>No new metrics were proposed. However, the group suggested changes in the wording of the existing metrics, specifically "Challenges of meeting safety requirements" rather than "Relative Safety Management Challenge".</u>

It was agreed (after much discussion and deliberation) that the safety metric was a very difficult if not impossible metric to define at the fuel cycle level. However, the group also agreed that a "safety" metric is required for completeness.

The group discussed the concern that the metric could be misused or misunderstood to be whether one fuel cycle is safer than another. The group concluded that it *is* acceptable to

say that new technologies are safer than those operating today – the example of Gen III/III+ reactors versus those operating today was specifically mentioned.

The group expressed concern that using simply "*Manageable*" applied across the fuel cycle would not sufficiently differentiate or cover all of the major hazards and issues in the fuel cycles.

A scale with 3 levels had been proposed by the EST that required consideration: A = Less challenging to manage than the risks of this type of facility under the current fuel cycle; B = Equally as challenging to manage as the risks or this type of facility under the current fuel cycle; C = More challenging to manage than the risks of this type of facility under the current fuel cycle. Questions were raised as to how to score a "Facility Type" that does not exist in the base-line fuel cycle, e.g., since reprocessing does not exist in a once-through fuel cycle, would the EST assign "C" (*More Challenging to Manage*) against that stage? The group agreed that this approach results in a correlation between number of additional fuel cycle steps and the number of "more challenging" scores (i.e. "C"s) that will result. The group also expressed concern that the wording of the scale was open to interpretation *viz a viz* are we looking to compare the challenge in this stage of the fuel cycle with *anywhere* else in the fuel cycle versus any fuel cycle *internationally*? The group recommended that the word "current" should be changed to "existing" in the description of the metric scoring. The group also indicated that the EST needs to address how to score reprocessing and whether it would be scored against current U.S. practice or against international experience.

The group questioned whether transportation is included in the safety metric. The EST representatives explained that at the fuel cycle stage this is too much detail and that there is currently no information in the Fuel Cycle Data packages (FCDPs) etc., to enable assessment to be done (e.g., are all facilities co-located?).

The group challenged under what circumstances an "A" (i.e., *Less Challenging to Manage*) rating would be assigned. For example, if a technology was new to the United States, then this will introduce "more challenges". However, some fuel cycles would not need enrichment, or mining, and would therefore score an "A". It was suggested that the EST needs to ensure consistency in the approach.

The group also contemplated how to interpret differences in the Safety score. "Not all 'Cs (*More Challenging to Manage*)' are created equally" was the phrase discussed. It was agreed that not all "C" should be scored equally as some of the challenges to address safety will be greater than others, but at this time a weighting is not possible; e.g., reactor "C" is always more important than a fuel fabrication "C". The group discussed the analogies between the "Safety" and the "Proliferation Risk" metrics and how identifying a "C" highlights the weakest point in fuel cycle (analogous to "proliferation risk"). The group was unable to agree as to whether it is then appropriate to sum up the numbers of A, B and C scores. It was agreed that as the intent is to inform on relative challenge at this time, then greater level of detail is needed later, but not appropriate at this time.

SUMMARY OF DISCUSSION, BREAK-OUT GROUP 2

Criteria:

- Nuclear Waste Management
- Environmental Impact
- Resource Utilization.

Participants:

First Name	Last Name	Company
Brent	DIXON	Idaho National Laboratory (Scribe)
Bo	FENG	Argonne National Laboratory
Fausto	FRANCESCHINI	Westinghouse
Massimiliano	FRATONI	The Pennsylvania State University
William	HALSEY	Lawrence Livermore National Laboratory (co-Chair)
Kathryn	HUFF	Argonne National Laboratory
Taek K.	KIM	Argonne National Laboratory
Steven	KRAHN	Vanderbilt University
Robert	MACKINNON	Sandia National Laboratories
Nigel	MOTE	US Nuclear Waste Technical Review Board
Mark	NUTT	Argonne National Laboratory
Candido	PEREIRA	Argonne National Laboratory
Bojan	PETROVIC	Georgia Institute of Technology
Christopher	PHILLIPS	Energy Solutions LLC (co-Chair)
Siegfried	STOCKINGER	Department of Energy
Peter	SWIFT	Sandia National Laboratories
Pavel	TSVETKOV	Texas A&M University
John	VIENNA	Pacific Northwest National Laboratory
William	WEBER	University of Tennessee
Abdellatif	YACOUT	Argonne National Laboratory
Won Sik	YANG	Purdue University
Choong-Shik	YOO	Washington State University

Summary of Breakout Session

The first breakout session of the group began with the material provided in the plenary session. From there, participants took each of the three criteria and discussed the draft metrics that have been proposed. While addressing the adequacy of the draft metrics, these discussions returned several times to the distinction between evaluating fuel cycles and evaluating specific technologies and implementation pathways. The second breakout

session revisited open issues from the first session and added discussion of the metric usage. In general, the basic structure of the metrics was understood and accepted – while constructive suggestions were provided to improve clarity, precision and transparency of the metrics. Several open issues were suggested for further consideration, without specific recommendations.

Nuclear Waste Management

Draft Criterion Definition: Management of the radioactive wastes requiring disposal, including any spent nuclear fuel (SNF), high-level waste (HLW), excess uranium (RU/DU) and low-level waste (LLW).

Draft Metrics:

- Mass of SNF+HLW disposed per energy generated *(t/GWe-yr)*
- Activity of SNF+HLW (100 years) per energy generated *(MCi/GWe-yr)*
- Activity of SNF+HLW (100,000 years) per energy generated *(MCi/GWe-yr)*
- Mass of DU/RU disposed per energy generated *(t/GWe-yr)*
- Volume of LLW per energy generated *(m^3/GWe-yr).*

Discussion:

It was noted that excess recovered thorium (Th) should be included in the definition of the mass disposed, particularly for fuel cycles that propose the disposal of recovered Th.

There was significant discussion as to what is a fundamental characteristic of a fuel cycle versus an engineering design property for a specific implementation alternative for that fuel cycle. For example, decay heat of a waste stream (normalized to energy production) is a physical characteristic of the material flow within the fuel cycle, while the specific heat output for a disposal container is an engineering design choice for an implementation alternative. Similarly, mass of initial heavy metal (iHM) is a fuel cycle characteristic, but fuel volume is a fuel design property.

The basic division into three waste types (SNF+HLW, RU+DU+Th, LLW) was discussed along with alternative divisions. In general, the division was understood and accepted.

The important issues for waste management were discussed, such as mass, volume, activity, heat generation, radiotoxicity, key radionuclides, disposal isolation performance, waste form loading, etc. It was agreed that some of these are more fundamental measures for a fuel cycle and others are implementation details (although still very important to disposal). There was discussion of fission product driven issues versus actinide driven issues. The decision not to assess specific disposal pathways and environments was discussed, and understood as an implementation decision (wastes from any fuel cycle could be disposed of in any reasonable environment).

The mass of SNF was readily understood in terms of iHM. Discussion of cladding and hardware, as well as other fuel forms (oxide/metal, TRISO, molten salt, etc.) resulted in no suggested change. The proposal to use a representative mass for a HLW form led to discussion of waste form loading and form alternatives. Use of a more fundamental measure was suggested.

The issue of SNF/HLW volume was discussed at length. It was agreed that volume is an important design constraint for geologic disposal. However, it is not a characteristic value for a fuel cycle. Volume of fuel is dependent on the fuel design, and could vary as much within most fuel cycles as it could between fuel cycles. For example, once-through LEU in a thermal spectrum could use many different fuel form alternatives – each with a different effective volume for direct disposal. In addition, many other fuel cycles could use a similar range of fuels. Similarly, HLW volume depends on the specific waste form used and the waste loading that is chosen for implementation. A wide range is possible for a given fuel cycle with HLW, and most could be used over a range of fuel cycles. This implementation variability makes volume of SNF/HLW a poor metric for a fuel cycle. By comparison, the mass flow is more characteristic of the nature of the fuel cycle and what the fuel cycle does with nuclear fuel materials.

Several of the draft metrics use activity at a specific time (after discharge from the reactor), and it was discussed that this was a surrogate for other potential metrics, such as heat generation, handling hazard, radiotoxicity or repository dose potential. There was concern that heat generation was not specifically included in the metrics, as it is a common design driver for a geologic repository. The trade-off of using activity as a surrogate for heat and hazard versus using heat as a surrogate for activity and handling difficulty was discussed, again reaching the question of the relative weighting between actinide versus fission product content. No clear preference for one approach over the other was found.

The time scale for disposal considerations was discussed, primarily in relation to the proposed 100 and 100,000 year metric proposals. The rationale for the times was discussed, along with alternative time, and alternative measures, such as 'the cross-over time between actinide and fission product decay heat'. In the end, the proposed times were understood, and generally accepted as adequate.

The question of explicitly calling out radionuclides of potential importance to long-term isolation versus including all radionuclides was discussed for the long-time metric. Ultimately, the activity of radionuclides of importance to disposal in any potential environment (and including disruptive events) is not significantly different from the activity of all radionuclides remaining. Ultimately, it becomes a question of optics – being comprehensive versus focusing on disposal importance.

The ability to determine LLW volume (or mass) for fuel cycles was recognized as a challenge, and that this would by necessity be an estimate based on number and types of processes included.

Suggestions:

- Consider a mass balance based measure for HLW mass rather than an assumed waste loading. (An example could be iHM minus material recovered for re-use or separate disposal.)
- Consider using a heat generation measure. It is similar in nature to the activity measure and specifically acknowledges the issue of heat for disposal. It was discussed and accepted that using heat in place of activity would shift the metric to somewhat more emphasis on actinides compared to fission products (as they tend to generate more heat for a given activity).
- Consider defining the *long term activity* (100,000 year) as activity of all radionuclides of potential importance to geologic isolation performance.
- Include recovered thorium with RU and DU, and clarify that it is RU+DU.
- Tie the discussion of what is included and not included in the criterion back to the questions asked in the Evaluation and Screening Charter.
- Consider computing the years until the activity decays back to the level of original uranium levels as it could be helpful in communicating the different repository impacts in a way understandable to the public.

Other Notes:

- It was noted that transportation was not included in this criterion. Discussion acknowledged that this was an implementation specific feature, but still important.
- It was noted that three of the five metrics addressed SNF+HLW. In general, it was felt that this is the most important waste type, and this focus was appropriate.
- Special waste streams such as transmutation targets for minor actinides or specific fission products were noted, and it is likely that these will be addressed in the analysis as an additional evaluation – as something that could be added to many different fuel cycles.
- It was noted that the United States does not have an implemented disposal pathway for the reference case.
- Combining RU and DU may unfairly penalize DU. However, there is no current disposal path for large quantities of either of them, and as such, the relative disposal challenge is not clearly definable. Sensitivity studies on the weighting of this metric may advise whether this potential difference warrants further consideration.
- The challenge for evaluating the metrics was discussed, with no specific suggestions.

Environmental Impact

Draft Criterion Definition: The impact to the environment from all activities related to the civilian nuclear energy system.

Draft Metrics:

- Land Use per unit of energy production *(km^2/GWe-yr)*
- Water Use per unit of energy production *(ML//GWe-yr)*

- Radiological impact - total estimated worker dose per unit of energy production (Person-mSv/GWe-yr)
- Chemical impact - chemical hazard index per unit of energy production *(Hazard Index(HI)/GWe-yr)*
- Carbon impact - CO_2 released per unit of energy production *(Mt/GWe-yr).*

Discussion:

In general, the proposed metrics were understood as the subset of environmental concerns that are potential measures for fuel cycles. The challenge to applying these metrics (or others) to fuel cycles that have never been designed or built was discussed.

There was discussion on whether CO_2 impact is even an appropriate metric for comparing nuclear energy fuel cycle, as it is typically used to inter-compare different energy sources, and nuclear will typically be a low carbon alternative regardless of the fuel cycle. It was also discussed whether it would be more appropriate to use energy return on investment (EROI) rather than CO_2 impact. It was pointed out that CO_2 calculation approaches are more mature than EROI approaches. However, EROI has additional implications not captured by CO_2 impact – EROI captures CO_2 impacts, but not the other way around. It was noted that calculations of future CO_2 emissions would require assumptions about the technologies used, such as assumptions about future use of fossil fuels for mining. Potential emission of other greenhouse gases was also discussed, but no suggestion was made for their inclusion.

Thermal emissions were discussed, possibly as a replacement for or in addition to water usage. Thermal heat rejection is likely to be the dominant use of water in many fuel cycles. However, both the water intensity of heat rejection and the environmental importance of heat rejection are location and engineering design specific. In general, it is likely that both will end up being a design optimization to minimize cost. It was suggested that thermal emission may be a more fundamental characteristic than water use, but neither is technology independent.

The draft metric on radiological impact proposes worker dose, but not public dose. This was seen to potentially invite the interpretation that public safety was not considered important. However, the group discussed the ability to estimate worker dose for fuel cycle processes based on regulatory requirements versus the inherent location specific nature (and uncertainty) of public dose – particularly for processes that have never been implemented. Several alternative approaches were discussed. It was suggested that it be made clear that the worker dose metric is included as a more readily evaluated leading indicator for potential public dose.

Suggestions:

- Consider whether CO_2 emission is a valid metric, or whether there is a more fundamental measure for fuel cycles.

- Consider replacing water use per unit of energy production with thermal emission per unit of energy production or whether to use both.
- If worker dose is being used as a 'leading indicator' for potential public exposure, then communicate this position effectively.

Resource Utilization

Draft Criterion Definition: The natural fuel resources required per unit of power production from the civilian nuclear energy system.

Draft Metrics:

- Natural uranium required per unit of energy production (*t/GWe-yr)*
- Natural thorium required per unit of energy production (*t/GWe-yr).*

Discussion:

There was discussion as to whether additional materials in the fuel cycle (beyond heavy metal), or even other resources (such as repository space) should be considered. The argument for focusing on fuel resources is that this is the primary issue that is thought of when the topic of *nuclear fuel cycle resource utilization* is raised. It is seen as a question of *is there enough fuel for nuclear energy to provide a significant energy source to society* and is the fuel resource used effectively. <u>In general, the rationale for focusing this criterion on fuel resources was understood and accepted.</u>

Suggestions:

- Consider whether there are any other important or strategic resources that should be included.
- Look at the use of any resource relative to other nuclear fuel cycles, not to world availability.

SUMMARY OF DISCUSSION, BREAK-OUT GROUP 3

Criteria:

- Financial risk and economics
- Development and deployment risk
- Institutional issues.

Participants:

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Jack	CLEMMENS	Shaw
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Edwin	MOORE	Savannah River National Laboratory
Paul	MURRAY	AREVA (co-Chair)
Brian	OAKLEY	Scully Capital
Paul	TURINSKY	NC State University and US Nuclear Waste Technical Review Board

Common Themes Related to All Three Criteria

Several common themes emerged throughout the two breakout session discussions. These themes were related to three aspects of the criteria set being discussed: (1) the general assumption that the EST is evaluating a fully implemented system in equilibrium does not apply for two of the criteria considered here (see next paragraph), (2) the three criteria all cover some aspect of the development-to-full scale deployment process, and the participants felt that additional clarity is needed about which parts of that process are covered by each of the criteria, and (3) there are aspects of these three criteria (as well as other criteria not included in Break-out Group 3) where participants felt that input from industry and utilities would be useful to the evaluation process (i.e., for calculation of the metrics). They encouraged the EST to seek that input.

The group indicated that for "Development and deployment risk" and for "Institutional issues", the assumption of a fully deployed system at equilibrium does not apply. These criteria are for "transitional" scenarios aimed at identifying potential challenges to implementation that would make a fuel cycle more or less promising. Participants emphasized that this distinction needs to be made clear, and suggested that the EST consider how the combined results of the evaluation and screening be presented in light of this difference in assumptions.

It was not clear to the breakout group participants where the EST intends to draw the "boundaries" between different stages of development, deployment, and full-scale implementation in equilibrium, and which of those stages are relevant to each of the three criteria discussed by this group. This issue was raised during the discussion of each of the three criteria considered, because the participants felt that further clarity was necessary to understand whether the metrics might double-count some aspects of the process or whether there are gaps in the metrics. A specific suggestion was made for how to clarify the stages and handoffs in the process:

- Step #1/Handoff #1: All research and development work through development of an engineering-scale integrated prototype. This is work that would typically be supported by government-funded R&D and the existing "development risk" metrics address issues up to Handoff #1 (see further discussion below)
- Step #2 / Handoff #2: All work required to go from an engineering-scale integrated prototype to a commercially deployable system. The group suggested that there is a gap in the metrics, in that this aspect of development and deployment is not addressed (further discussion below)
- Step #3: Work required to go from a commercially deployable system to a full-scale equilibrium system. It was unclear to the group whether the "Financial risks and economics" metrics adequately address this step (e.g., by including the commercial development costs).

Financial Risk and Economics

Draft Criterion Definition: The economics (cost factors) of the mature deployed system, including siting, construction, and operation of facilities, including consideration of the financial risk.

Draft Metric:

- Levelized Cost of Electricity at Equilibrium (LCAE).

Discussion:

Inclusions and exclusions were discussed in depth, with particular focus on the common theme #2 described above, the need for clarity about what costs within the development and deployment process are included in the metric. Per the discussion above and the criterion definition, the group concluded that LCAE includes only the costs of the "mature deployed system." Given that clarification, no changes were suggested for the Financial Risk and Economics Metric.

There was more discussion on how LCAE would be measured or calculated and how it would be used. Uncertainty in LCAE was emphasized, and the group recommended that the EST (1) not attempt to summarize LCAE with a single number, include at least a range or a full probability distribution on costs as part of the evaluation result, (2) think through and clarify how to include adequate recognition of the impact of technology uncertainty in the

LCAE estimates, recognizing that there is greater uncertainty in the costs for fuel cycles for which no technologies have yet been developed than for fuel cycles that can use some existing technologies.

Several additional suggestions were made to clarify definitions, inclusions and exclusions, and to ensure compatible assumptions are made across criteria when conducting the evaluation. Suggestions included:

- Clarify the definition of "financial risk," and "normal utility business risk" with examples.
- Clarify what costs will be included in the LCAE calculation (e.g., does it include costs for interim storage? for handling process wastes? How are operating costs handled, especially for novel systems?).
- Identify who will be involved in making the necessary cost estimates (e.g., Used Fuel Disposition (UFD) campaign and industry involvement in estimating waste management costs?).
- Describe how the EST will ensure compatible assumptions / estimates of the inputs that affect multiple criteria. For example, estimates of the amount of nuclear waste generated inform both the nuclear waste management criterion and the costs of disposal.
- It seems likely that some technology assumptions will have to be made in order to estimate costs. The EST should be clear about where such assumptions are being made.
- Consider whether it makes sense to have different discount rates for government investments versus commercial investment within the LCAE calculation.

Finally, the group noted that it will be very challenging to estimate or confirm the estimates of costs for fuel cycles, technologies, and facilities that have never been built. They also recommended that the name of this criterion be changed to "economics and financial risk" to better reflect the emphasis on economics in the metric (although it was noted that the specific criteria labels were provided to the EST as part of its charter and may not be open for change by the EST).

Development and Deployment Risk

Draft Criterion Definition: The challenge of bringing to maturity the required technologies for a civilian nuclear energy system, including the time and cost required for successful research and development, and the ability to deploy licensable systems.

Draft Metrics:

- Development time
- Development cost
- Compatibility with the existing infrastructure
- Existence of NRC regulations for the fuel cycle and familiarity with licensing.

Discussion:

There was significant discussion among the group about what is included in consideration of development and deployment risk (as well as economics and financial risks), leading to the recommendations described above under common theme #2 that the EST should clearly define each stage in the development-to-full-scale-equilibrium system process and identify what factors are included in the "deployment" part of this criterion.

Participants noted that the current definition of the metric does not include deployment risks beyond engineering-scale prototypes, and that this is a gap. They suggested the addition of metrics related to the time and costs to go from an engineering scale prototype ("handoff #1 as defined above) to a fully deployed system in equilibrium be considered as metrics to address this gap. Elements of process for developing these estimates were proposed: identify the number "steps" (generations or prototypes) that would be required between "now" and handoff#1, and between handoff #1 and handoff #2, and use that understanding to develop cost/time estimates.

In terms of two of the metrics, development time and development cost, the group raised two issues for consideration: (1) whether and how the probability of successful development could be captured within the metrics, and (2) whether to consider timing "thresholds." As an example, they discussed implementing the development time metric in terms of the likelihood of successful development by specific time points (e.g., 10, 20, 50 years).

The group noted that this evaluation will be challenging, with particularly challenging steps being:

- Identifying potentially required technologies (requires some technology assumptions), their current Technology Readiness Level (TRL) and the time and cost required to get those technologies to TRL 6.
- Whether and how to consider technology development in other countries within this assessment
- How to extrapolate the individual technology assessments to estimate the time and cost required for an integrated fuel cycle to be at an appropriate technology readiness level.

Finally, it was suggested that the EST explicitly include some estimate of commercial viability as a metric, either within this criterion or within the Institutional Issues criterion. Specific metrics were not proposed.

Institutional Issues

Draft Criterion Definition: The availability or ability to create the supporting infrastructure to deploy a civilian nuclear energy system, including the industrial infrastructure, qualified personnel, and the existence of regulations for licensing.

Draft Metrics:

- Compatibility with the existing infrastructure
- Existence of NRC regulations for the fuel cycle and familiarity with licensing.

Discussion:

The bulk of the discussion regarding the "institutional issues" criterion revolved around whether and how "public" or "stakeholder" acceptability or the perception of a fuel cycle option should or could be included within the criterion definition and metrics. Ultimately the group did not recommend that public or stakeholder acceptability be added as a metric. Instead, they recommended that the definition and description of *Institutional Issues* be clarified by avoiding the term "stakeholder" in discussion of the institutional issues criterion and emphasizing institutional barriers to implementation. Various approaches for increasing public and stakeholder acceptance of the evaluation process itself were discussed, all involving seeking direct input from the stakeholders on aspects of the evaluation of fuel cycles (weighting of metrics for a criterion, and on the combination of the criteria into an overall score).

The methodologies by which the two proposed metrics are to be implemented were not clear to the group. It was recommended that "compatibility with existing infrastructure" include at least all of the following types of infrastructure: physical infrastructure, human resources, market mechanisms, other systems of electricity generation.

Finally, it was also suggested that the EST explicitly include some estimate of commercial viability as a metric, either within this criterion or within the Development and Deployment Risk criterion. Specific metrics were not proposed, but the following set of questions was hypothesized as being relevant to commercial viability of implementation of a fuel cycle:

- Are the required facilities and systems licensable?
- Can they be sited?
- Is there a stable regulatory environment in which utilities can operate?
- Why should "we" (industry and the utilities) build and implement the fuel cycle systems?

Attachment D

U.S. DOE Informational Meeting on Nuclear Fuel Cycle Evaluation Metrics
Argonne National Laboratory
November 8-9, 2012

LIST OF MEETING PARTICIPANTS

First Name	Last Name	Company
Sven	BADER	AREVA
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Attachment E

U.S. DOE Informational Meeting on Nuclear Fuel Cycle Evaluation Metrics
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ACRONYMS, ABBREVIATIONS AND SYMBOLS

COEX	Co-extraction
DOE	U.S. Department of Energy
DU	Depleted uranium
E&S	Evaluation and Screening
EROI	Energy Return on Investment
EST	Evaluation and Screening Team
FCDP	Fuel Cycle Data Package
FCO	Fuel Cycle Options – Systems Analysis & Integration
FOM	Figure of Merit
HLW	High-level waste
iHM	Initial heavy metal
IND	Improvised Nuclear Device
IRT	Independent Review Team
LCAE	Levelized Cost of Electricity at Equilibrium
LLW	Low-level radioactive waste
LWR	Light-water reactor
LEU	Low enriched uranium
MOX	Mixed Oxide
NRC	Nuclear Regulatory Commission
Pu	Plutonium
PUREX	Plutonium Uranium Extraction
R&D	Research and Development
RDD	Radiological Dispersion Device
RU	Recovered uranium (from spent nuclear fuel)
SNF	Spent nuclear fuel
Th	Thorium
TRL	Technology Readiness Level
U	Uranium
UFD	Used Fuel Disposition