Qualitative and Quantitative Metrics for Evaluating the Nuclear Fuel Cycle

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A decision making model to investigate alternatives to the proposed current approach to long term management of used nuclear fuel has been developed. The model utilizes the analytic hierarchy process (AHP), which is a multiple criteria decision analysis (MCDA) method, to weight different criteria that are relevant to the decision through pair-wise comparisons. A difficulty with assessing any nuclear fuel cycle is determining the metric for each criterion that will be used in the evaluation. Many quantitative metrics exist already, such as radiotoxicity, uranium utilization, and mass of waste, etc. However, the quantitative aspects are inherently limited and give only a specific viewpoint towards the fuel cycle. Public perceptions have a very real associated cost and disregarding it can lead to delayed progress or a complete impasse for any project.

In order to incorporate public opinion, among other qualitative aspects, into the selection of a fuel cycle, appropriate metrics need to be developed. Such qualitative criteria include public acceptance, legal resolution, and improved energy policy leadership for the government. The metrics for these qualitative criteria need to be such that they appropriately convey an aspect that is missed in the quantitative assessment. Although great effort has been made to try to include the important objectives of a nuclear fuel cycle directly from the general public, ultimately this analysis and the metrics that were developed are from the perspective of a nuclear engineer. Aspects of all criteria are also discussed and a finalized list of criteria and metrics are presented.

I. INTRODUCTION

One of the main impediments facing the nuclear industry in the U.S. is the continued unresolved nature of the back end of the fuel cycle, specifically when, where, and how the used nuclear fuel will be disposed of.[1] Despite the foundation laid by the legal framework of the Nuclear Waste Policy Act (NWPA) that specifies the final disposition of spent fuel, public policy continues to vacillate between support and opposition.[1] To attempt to solve the persistent issue, many different decision analysis frameworks have been implemented; however, the analysis of selecting a fuel cycle or selecting nuclear power as a fuel source over other fuel sources tend to focus on quantitative data.[2,3,4,5] Although excellent quantitative data is crucial to making sound decisions, limiting the scope of the decision space to only the range of definite quantities fails to account for aspects that could rival the importance of quantitative metrics or even supersede them.

In generating criteria, also called attributes or objectives, by which to evaluate different alternatives, it is important to thoroughly asses each one based on certain requirements. The five recommended requirements, according to Keeney, are that the criteria are *unambiguous, comprehensive, direct, operational* and *understandable*.[6] In this paper, qualitative and quantitative criteria and their corresponding metrics will be developed which have these five requirements.

II. IMPORTANT REQUIREMENTS OF CRITERIA

Selecting criteria that include the previously mentioned five important factors is of paramount importance when communicating the complexities of nuclear engineering to a member of the general public. Of special importance when eliciting values or priorities from members of the general public is that the factors are both *unambiguous* and *understandable*. That a criteria should be *unambiguous* is to say that the consequences from that criteria should scale accordingly with the levels associated with that criteria.[6] Additionally, the greatest effort must be given to avoid vagueness and imprecision.[6] This can be likened to unnecessarily grouping values when the value itself supplies the necessary information; for example there is a loss of information if one was to group people according to height in constructed categories such as *tall* if their height is greater than 180 cm (5'11") and *short* if their height is less than or equal to 180 cm. The reason this is ambiguous is because it artificially evaluates that someone who is 181 cm in height is *tall* while a person who is 180 cm is *short*, despite the difference of only one centimeter. This grouping is inappropriate since the height difference between two individuals is already clear just by giving their measured heights. To have criteria that are *unambiguous* is especially important so that proper comparisons can be made between the different criteria to assess their relative importance.

That the criteria have the property of being *understandable* is of primary interest when communicating a decision regarding nuclear science to the general public. Terminology and concepts in engineering in general, especially in nuclear engineering, are not ubiquitous within the vernacular. Thus to define a criterion, such as radiation exposure, in terms of its scientific units, such as the millisievert (mSv), means essentially nothing to a member of the general public. That is because the scientific unit is a way of quantifying the effects of radiation exposure in a more measurable manner at the expense of widespread clarity. It may be more transparent to measure the risks of radiation exposure, not in millisierverts, but rather in what they tangibly represent, that is the increased probability of developing cancer.[3] However, this is not without its own difficulties, considering the scientific controversy in relating low-doses of radiation to a certain number of cancers induced. Despite the fact that the current model for converting dose into risk is inherently unverifiable at low-doses since the predicted instances of cancer are fewer than the natural statistical variation of normally occurring cancer,[7] it is still more appropriate when communicating to the general public to use a concept that they will understand, such as cancer. To understand the need for this, consider eliciting value judgments about two criteria, by asking, "Which is more important, lowering operating costs from two million dollars to one million dollars per year or lowering radiation exposure from 3 mSv to 1 mSv per year?" Not many people would be able to give you a meaningful answer that represents their actual values, since the millisievert is foreign to most. Compare this to asking "Which is more important, lowering operating costs from two million dollars to one million dollars per year or reducing the number of fatal cancers induced from radiation exposure from 15 people per million to 5 people per million?" The second comparison is much more *understandable* and gives a clear reason why the value trade-off needs to be made. When evaluating the perceptions of the general public having criteria that are *understandable* to the general public cannot be stressed enough.

What was just illustrated was that the value of the scientific unit is a means of quantifying an effect, but it is not always representative of the actual important effect itself. Lowering the measured radiation exposure is what Keeney would call a *means objective*, whereas lowering the number of radiation induced fatal cancers would be a *fundamental objective*.[8] To find a fundamental objective from a means objective, one simply must ask of each developed criteria "Why is this important?" and this should drive the answers to more fundamental regions.[8] One must repeat the question until one reaches a *strategic objective*, that is a criteria whose realization is only partly related to the decision context.[8] For instance maximizing public health and safety would be the strategic objective of minimizing the number of induced cancer cases from radiation exposure fundamental objective since there are a multitude of criteria that effect public health and safety outside the scope of the nuclear fuel cycle. In this paper we will henceforth refer to these as *means criteria*, *fundamental criteria*, and *strategic criteria*.

Additionally, the criteria need to be *comprehensive*, that is covering the full range of consequences of a criteria, *direct*, that is describing in a definite manner the consequences of interest, and *operational*, that is the information required for the evaluation of the criteria can actually be obtained.[6] Finally, since the model would be utilizing linear functions to develop the final weights for the criteria, an additional requirement was needed to maintain the validity of this assumption. This requirement is that each criterion be mutually exclusive of the rest of the criteria. Keeping in mind the previous requirements, the qualitative and quantitative criteria and metrics were developed to evaluate the nuclear fuel cycle in the United States.

III. INITIAL CRITERIA GENERATION

To begin to evaluate multiple nuclear fuel cycles against common criteria that incorporate both qualitative and quantitative metrics an extensive literature review was done. In order to supplement this review with a better understanding of individuals' perceptions toward the nuclear fuel cycle and nuclear energy in general, three focus groups and a series of surveys were conducted at a large university in the southeastern U.S. A final step in generating the initial criteria was brainstorming between members of the research group. An initial list was constructed and can be seen below in Table I. The hierarchies were separated into four sections pertaining to the benefits, opportunities, costs, and risks involved in choosing a specific fuel cycle and can be seen in Table I.

III.A. Benefits

The following were the definitions for the benefits criteria: *Disposition Flexibility*: The benefits of the degree to which the fuel cycle allows for waste to be disposed of with flexibility in timing, transportation scenarios, and disaster situations. *Fuel Requirement Reduction*: The benefits of the fuel cycle reducing the new mined fuel requirements. *Infrastructure Development*: The benefits of developing new transportation routes, i.e. interstate railways. *Legal Resolution*: The benefit of the U.S. fulfilling its legal and contractual obligations to the utility companies as well as fulfill previously passed legislation. *Local Improvements*: The benefits of the influx of jobs, labor, and money in the local area from any required facility (repository, reprocessing facility, etc.). *Nuclear Political Stability*: The benefits of stability in the politics after having a clear path defined for spent fuel. *Pollution & Emissions Reduction*: The benefits of reducing the overall pollution and emissions.

III.B. Costs

The following were the definitions for the costs criteria: *Facility Construction & Maintenance*: Cost associated with the construction and maintenance of any required facility (repository, reprocessing facility, etc.). *Infrastructure Development*: The monetary cost of developing the infrastructure required for the fuel cycle (human resources development, support facilities). *Transportation*: Costs associated with the transportation of the used fuel, (interstate railways, trucks, barges, etc.) including their maintenance. *Legal Fees & Fines*: Costs accrued by legal fees and fines. *Licensing*: Costs associated with the licensing of new technologies and methods. *Proliferation Prevention*: The cost associated with implementing procedures and policies aimed at preventing proliferation of nuclear materials. *Waste Amount*: The cost associated with disposing of the sheer amount of the waste developed.

III.C. Opportunities

The following were the definitions for the opportunities criteria: *American Nuclear Development*: The opportunity of utilizing American resources, technology, labor

Benefits	Costs	Opportunities	Risks
Disposition Flexibility	Facility Construction & Maintenance	American Nuclear Development	Feasibility
Fuel Requirement Reduction	Infrastructure Development	Decommissioning Allowance	Potential Future Burden
Infrastructure Development	Transportation & Maintenance	Energy Policy Leadership	Proliferation Potential
Legal Resolution	Legal Fees & Fines	Long-term Energy Security	Public Perception
Local Improvements	Licensing	Promote Nuclear Industry	Radiotoxicity
Nuclear Political Stability	Proliferation Prevention	Technology Development	Supply Availability
Pollution & Emissions Reduction	Waste Amount	U.S. Government Competence	Waste Escape Accidents

Table I. Initial Criteria Hierarchies

and establishing nuclear as an American energy source. *Decommissioning Allowance*: The opportunity of permanently decommissioning obsolete and shut down nuclear facilities. *Energy Policy Leadership*: The opportunity that the fuel cycle would allow the U.S. to gain back respect internationally in terms of energy policy leadership. *Long-term Energy Security*: The opportunity that the fuel cycle would allow electricity production to be secure and reliable for many years. *Promote Nuclear Industry*: The opportunity that the nuclear industry can begin to grow with a resolved fuel cycle; (greater youth recruitment, new power plants constructed). *Technology Development*: The opportunity that the fuel cycle will cause new technology to developed. *U.S. Government Competence*: The opportunity that the selected fuel cycle improves U.S. Citizens' attitude toward the U.S. government's competence.

III.D. Risks

The following were the definitions for the risks criteria: *Feasibility*: The risk of the fuel cycle not being technically feasible. *Potential Future Burden*: The risk of maintaining the fuel cycle for future generations. *Proliferation Potential*: The risk of the potential for nuclear materials being diverted from their proper channels. *Public Perception*: The risk of the negative public perceptions and responses to the fuel cycle. *Radiotoxicity*: The risk of the radiation activity of the spent fuel and exposure possibilities from the fuel cycle. *Supply Availability*: The risk of the availability of materials and fuel to ensure proper operation of the fuel cycle. *Waste Escape Accidents*: The risk of the potential for the waste to escape from its desired locations because of accidents.

IV. THE ANALYTIC HIERARCHY PROCESS

In order to evaluate the criteria in a meaningful way, the analytic hierarchy process (AHP) was utilized. AHP, as developed by Thomas Saaty in 1980, is a multiple criteria decision analysis (MCDA) process utilizing hierarchies, pair-wise comparisons, and consistency analysis to obtain weights for decision alternatives.[9] A brief overview of the process is as follows: first, the decision goal is broken up into its constitutive criteria, some of these are really sub-criteria and the criteria and subcriteria are rearranged into a hierarchy. Next, each criterion on the same hierarchy level is compared to each other based on their relative importance to the decision goal, and these values are used to populate a decision matrix.[9] A brief example of this would be something like: *Fuel Requirement Reduction* is twice as important as *Legal Resolution* in regards to the benefits of an optimum nuclear fuel cycle for the United States. It is not mathematically necessary to compare each criterion to one another, as the later comparisons should be determined by the former, e.g. if A is three times greater than B and B is two times greater than C, to be logically consistent, A must be six times greater than C. However, logical consistency is in general not inherent in people's decisions.[10] Thus each criteria is compared to one another and the consistency is evaluated through the use of two quantities. The first quantity is known as the consistency index (CI) and is as follows.

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{1}$$

where λ_{max} is the maximum eigenvalue of the judgment matrix, and n is the order of the matrix.[9]

The second quantity is the consistency ratio (CR) and is the ratio of the consistency index to a quantity known as the random index (RI).

$$CR = \frac{CI}{RI} \tag{2}$$

The random index is the average consistency index for a large number of randomly assigned judgment matrices.[9] For decisions with more than three criteria a consistency ratio less than 10% is recommended by Saaty.[9] To develop the overall weights, or priorities, for the criteria, the judgment matrix is normalized and each row averaged. The corresponding number represents the priority of that criteria.[9]

In this paper, we will primarily be utilizing the AHP consistency ratio to evaluate how well criteria are understood by survey respondents.

V. INITIAL CRITERIA EVALUATION

This list of initial criteria was taken to a large nuclear engineering and science conference, and conference attendees were asked to pair-wise compare the relative importance of criteria against each other. A sample of the pairwise-comparison survey that was handed out is shown below in Table II. The possible responses for the magnitude of importance are limited to the qualitative terms, *slightly*, *moderately*, *strongly*, *very strongly*, and *extremely*. Additionally, the respondents are free to write *equally important*. These were interpreted using a simple integer one through nine scale such that *equally important* = 1, *slightly* = 2, *moderately* = 3, *strongly* = 5, *very strongly* = 7, and *extremely* = 9, times more important. Collecting the responses and evaluating the consistency of the responses through the AHP, it was shown that a large percentage of the respondent's judgments failed to meet the consistency threshold of 10%. This trend can be seen in Table III.

It was concluded that a primary contributing factor to the high percentage of inconsistent responses was likely derived from the criteria not being well enough defined, and not containing the five desirable factors of criteria as previously mentioned. Some problems were determined to be vagueness in the previous definitions, having non-mutually exclusive criteria, and having criteria that are not relevant within the decision context. These problems are especially important to resolve considering the high inconsistency of the initial sample was mostly from individuals knowledgeable in the subject matter, which would be expected to make clear judgments. Since one of our primary audiences is the general public, it was expected to find a much larger inconsistency percentage among that population.

In order to understand which specific criteria were most likely ill-defined, an analysis of the geometric variance was done for each criterion at each consistency threshold. Since only the geometric variance of a comparison of two criteria can be determined, it was assumed that each of the criterion's relevant comparison's variances would be summed equally. So that when comparing *Disposition Flexibility* to *Legal Resolution* a geometric variance of 5.67 was found, this value would populate the first value for each criteria. Since seven criteria were present in each hierarchy, a total of six values would be determined. The arithmetic mean of these variances shows the variability associated with each criteria. For example the average variance associated with the first criteria, would be given in Eq. 3.

$$\bar{\sigma}_1^2 = \frac{\sum_{j=2}^{m} \sigma_{1,j}^2}{m-1} \tag{3}$$

Where $\bar{\sigma}_1^2$ is the average geometric variance associated with the first criterion, $\sigma_{1,j}^2$ is the geometric variance of the comparison of criterion 1 with criterion i, and m is the number of criterion, which in our case is 7.

This was done for each criteria and the results can be seen below in Table IV. It should be noted that a geometric variance of exactly 1 represents perfect alignment. There are two possible ways to interpret the reason for a criterion having a high geometric variance, the first being that the criterion is inherently controversial and that the spread in the data is due to this controversial aspect, or the second interpretation being that the criterion is defined in such a manner that any number of people can derive a different meaning from the same statement. The authors choose the second interpretation of high variance values since it is the only one that can be controlled. As such, all criteria were reevaluated with special attention paid to those with the highest average geometric variances.

VI. NEW CRITERIA

It was clear that the criteria needed to be refined so that they were unambiguous, comprehensive, direct, operational and understandable. After consulting external environmental and nuclear experts the following finalized criteria were decided upon.

In addition to extensively revising the definitions of the criteria, the labels for each definition were also changed. These changes can be seen in Table V.

VI.A. Benefits

The finalized definitions for the benefits criteria were changed as the follows: *Disposition Flexibility* was changed to *Disposal Flexibility* and the definition was changed to: The benefits of choosing a fuel cycle with the flexibility to accommodate the disposal of different quantities, types, and sizes of used fuel, existing currently or potentially available in the future. The reasoning behind this change was first, that the word 'disposition' was not understandable enough, and that the word 'disposal' was much more understandable and that there was no loss in meaning from using it instead. Secondly, the definition was expanded so that it is more operational since measuring number of fuel quantities, types, and sizes can be more easily done, than measuring flexibility in response to disaster situations.

The definition of *Fuel Requirement Reduction* was slightly changed to: The benefits of selecting a fuel cycle that reduces the need to mine or import additional nuclear fuel (i.e. uranium). This was to be more clear that uranium is what is mined, and that this also affects the amount that needs to be imported.

Infrastructure Development was changed to *National Infrastructure Development* and the definition was changed to: The benefits gained from the development of national infrastructure (i.e. interstate highways, railways, and support facilities) in connection with a selected fuel cycle. This was done to be more understandable and make this definition mutually exclusive from *Local Economic Development*.

The definition of *Legal Resolution* was slightly changed to: The benefit of selecting a fuel cycle that allows the U.S. Government to comply with previously passed legislation and fulfill its legal and contractual obligations to the utility companies in a timely manner. This was done to make clearer the timeliness of the criterion and to show that the primary legal issues are between utilities and the U.S. Government.

Local Improvements was changed to *Local Economic Development* and the definition was changed to : The benefit of selecting a fuel cycle that stimulates the local economy with job creation, tax revenue, and an infusion of money from new site workers entering the area due to the construction and operation of a required facility (i.e. repository, reprocessing facility, etc.). This major overhaul was done to establish mutual exclusivity with *National Infrastructure Development*, in addition to making the criteria much more understandable and comprehensive.

The criterion *Nuclear Political Stability* was removed since it was concluded that this concept was already adequately accounted for in the opportunities hierarchy. Additionally, the criterion *Pollution & Emissions Reduction* was expunged completely since it was determined that this

Criteria A	Criteria B	Which one is more important?	How much more important?
Disposition Flexibility	Fuel Requirement Reduction	*A*	*Moderately*
Disposition Flexibility	Infrastructure Development	*Equal*	*Equal*

Table II. Pairwise Comparison Example

	Sample Size				
Group	No Threshold	20% Inconsistency	15% Inconsistency	10% Inconsistency	Percent Reduction
Benefits	15	12	12	7	53%
Costs	11	9	8	7	36%
Opportunities	11	8	6	3	73%
Risks	11	6	4	3	73%
Total	48	35	30	20	58%

Table III. Sample Sizes of Surveys Collected at Large Nuclear Engineering and Science Conference

criteria is important only when evaluating between energy sources, i.e. coal, solar, nuclear, and not between fuel cycles, since the variation in pollution and emissions between fuel cycles is expected to be very low.

Two additional criteria were derived for the benefits criteria, the first being *Public & Political Acceptance*: The benefit of having public consensus that a selected fuel cycle satisfies the needs of society and provides "peace of mind" to both policy makers and the general public. The second being *Increase Technical Workforce*: The benefits of choosing a fuel cycle that promotes the training of more high-paid engineers, scientists, and technical professionals. With these changes it was determined that the benefits hierarchy was completed.

VI.B. Costs

The definitions for the costs criteria were changed to the following: *Facility Construction, & Maintenance* was changed to *Facility Construction, Operation, & Maintenance* and the definition was expanded to: The costs associated with the construction, operation and maintenance of any required facility (repository, reprocessing facility, etc.) for a selected fuel cycle. This was done to make the criterion more comprehensive.

The definition of *Legal Fees & Fines* was changed to: The costs of the legal fees and fines, paid by taxpayers, that are accrued by the U.S. Government from unfulfilled commitments during a selected fuel cycle's implementation schedule. This change was done to alleviate vagueness in the previous definition and emphasize who pays for the fees and fines.

The definition of *Licensing* was slightly changed to: The costs associated with the licensing of facilities, related technologies, and methods for a selected fuel cycle. This change makes the criterion more comprehensive.

The definition of *Proliferation Prevention* was changed to: The costs of implementing procedures and policies aimed at preventing the diversion of nuclear materials from a selected fuel cycle for non-authorized applications (i.e. weapons). This change was done so that the criterion is more understandable and less vague.

Hierarchy	Criteria	$\bar{\sigma}^2$
Benefits	Disposition Flexibility	3.93
	Fuel Requirement Reduction	3.01
	Infrastructure Development	2.80
	Legal Resolution	5.62
	Local Improvements	4.01
	Nuclear Political Stability	5.16
	Pollution & Emissions Reduction	5.35
Costs	Facility Construction & Maintenance	4.17
	Infrastructure Development	3.63
	Legal Fees & Fines	3.05
	Licensing	3.70
	Proliferation Prevention	4.01
	Transportation	3.66
	Waste Amount	3.79
Opportunities	American Nuclear Development	3.20
	Decommissioning Allowance	1.84
	Energy Policy Leadership	3.80
	Long-term Energy Security	3.93
	Promote Nuclear Industry	3.17
	Technology Development	3.92
	U.S. Government Competence	3.85
Risks	Feasibility	8.20
	Potential Future Burden	5.23
	Proliferation Potential	4.38
	Public Perception	6.63
	Radiotoxicity	3.90
	Supply Availability	4.30
	Waste Escape Accidents	5.66

Table IV. Average Geometric Variance for each Criterion

Infrastructure Development was changed to *Supplemental Infrastructure Development* and the definition was slightly changed to: The costs of developing the additional infrastructure (i.e. interstate highways, railways, and technical workforce) required for a selected fuel cycle. This was done to assure mutual exclusivity with the *Facility Construction, Operation, & Maintenance* criterion and to make the the criterion more comprehensive.

The definition of *Transportation* was slightly altered to:

Hierarchy	Initial Criteria	Finalized Hierarchy
Benefits	~~Disposition~~ Flexibility	*Disposal* Flexibility
	Fuel Requirement Reduction	Fuel Requirement Reduction
	Infrastructure Development	*National* Infrastructure Development
	Legal Resolution	Legal Resolution
	Local ~~Improvements~~	Local *Economic Development*
	~~Nuclear Political Stability~~	*Public & Political Acceptance*
	~~Pollution & Emissions Reduction~~	*Increase Technical Workforce*
Costs	Facility Construction & Maintenance	Facility Construction, *Operation*, & Maintenance
	Infrastructure Development	*Supplemental* Infrastructure Development
	Legal Fees & Fines	Legal Fees & Fines
	Licensing	Licensing
	Proliferation Prevention	Proliferation Prevention
	Transportation	Transportation
	~~Waste Amount~~	*Switching Policy*
Opportunities	American ~~Nuclear~~ Development	American *Economic* Development
	~~Decommissioning Allowance~~	
	Energy Policy Leadership	Energy Policy Leadership
	Long-term ~~Energy Security~~	Long-term Electricity Production
	~~Promote~~ Nuclear Industry	Nuclear Industry *Growth*
	Technology Development	*New* Technology Development
	U.S. Government Competence	U.S. Government Competence
Risks	Feasibility	*Technical* Feasibility
	Potential Future Burden	Potential Future Burden
	Proliferation Potential	Proliferation Potential
	Public ~~Perception~~	Public *or Political Rejection*
	~~Radiotoxicity~~	*Radiation Exposure*
	Supply Availability	Supply Availability
	~~Waste Escape~~ Accidents	Accidents *or Nuclear Material Release*

Table V. Change in Hierarchy Labels

The costs of the transportation of the used fuel in a selected fuel cycle (trucks, drivers, barges, trains, etc.). This change was done to make the criterion more comprehensive.

The criterion *Waste Amount* was removed since it was concluded that this concept was already adequately accounted for in the benefits and risks hierarchies.

Finally, the new criterion of *Switching Policy* was added with the following definition: The costs of switching from the currently selected fuel cycle to an alternative fuel cycle (i.e. workforce retooling, legislation, sunk costs). After these changes it was determined that the costs hierarchy was completed.

VI.C. Opportunities

The following are the definitions for the opportunities criteria: *American Nuclear Development* was changed to *American Economic Development* and the definition was changed to: The opportunity of selecting a fuel cycle that stimulates the national economy due to job creation and tax revenue. This was done to make the criterion more comprehensive by emphasizing the opportunities that a resolved fuel cycle would present to the U.S. as a whole and not simply to the nuclear industry. These changes were also necessary to make this criterion mutually exclusive of *Nuclear Industry Growth*.

The definition of *Energy Policy Leadership* was changed to: The opportunity that the U.S. becomes an international leader in energy policy (i.e. energy directives, programs, strategies, etc.) as a result of selecting a fuel cycle. This was done make the criterion more understandable by what is meant by leadership in the realm of energy policy.

The criterion *Long-term Energy Production* was changed to *Long-term Electricity Production* and the definition was altered to: The opportunity that a selected fuel cycle allows the U.S.to reliably meet electricity needs for the present and in the long-term future. The title and definition were changed to make the criterion less ambiguous, specifically that the scope of nuclear is within electricity production and not to energy as a whole.

The criterion *Technology Development* was changed to *New Technology Development* and the definition was changed to: The opportunity that research geared toward the development of a selected fuel cycle will lead to the creation of new technologies both related and unrelated to nuclear science. This change was made to make the criterion much more understandable, especially clarifying the fact that technology outside of the nuclear field can be developed and created.

The title of *Promote Nuclear Industry* was changed to *Nuclear Industry Growth* and the definition was altered to: The opportunity that selecting a fuel cycle would allow the U.S. nuclear industry to advance, expand and produce a greater amount of electricity more efficiently. This change was done to make the criterion more comprehensive and more understandable. Especially, that the fundamental criterion is to grow the nuclear industry and not simply to promote it.

The definition of *U.S. Government Competence* was changed to: The opportunity that choosing a fuel cycle would allow the U.S. government to be viewed by its citizens as competent in planning and implementing a major national project that solves a longstanding and persistent domestic issue. The change was done to make the criterion much less ambiguous and specify specifically what is meant by 'competence'.

The criterion *Decommissioning Allowance* was completely removed under the following reasoning; the opportunity to decommission a nuclear facility is one of the primary motivations of any nuclear fuel cycle, and the information gathered from the analysis of this criterion would not be largely differentiating between fuel cycles. With these revisions it was concluded that the opportunities hierarchy was finalized.

VI.D. Risks

The following are the definitions for the risks criteria: The criterion of *Waste Escape Accidents* was changed to *Accidents or Nuclear Material Release* and the definition was altered to: The risk of selecting a fuel cycle that has a greater potential for nuclear material to be released from power plants, storage containers, storage facilities, handling facilities, or transportation vehicles. This change was done to make the criterion more understandable, more comprehensive, and much less ambiguous.

The definition of *Potential Future Burden* was changed to: The risk of choosing a fuel cycle that manages the used fuel in a manner in which future generations must still deal with the final disposal of the used fuel. This change was primarily done to alleviate the ambiguities present in the previous definition.

The definition of *Proliferation Potential* was altered to: The risk of selecting a fuel cycle that has greater potential of having nuclear materials diverted for non-authorized applications (i.e. weapons). This change was done so that the criterion was more understandable and so that ambiguity would again be diminished.

The criterion *Public Perception* was changed to *Public or Political Rejection* and the definition was altered to: The risks of not having the majority agree that the selected fuel cycle satisfies the needs of society or provides "peace of mind" to either policy makers or the general public. The new title and definition are more understandable and are more operational compared to the previous ones.

The criterion *Radiotoxicity* was changed to *Radiation Exposure* and the definition was altered to: The risk of site-workers and the general public being exposed to radiation generated by the used nuclear fuel due to the selected fuel cycle. This change was to make the title and the definition more understandable and less ambiguous. This criterion may be broken down further into the exposure to just site-workers and the exposure to just members of the general public if further clarity is required.

The definition of *Supply Availability* was changed to: The risk of the fuel inventory being consumed faster than it can be replenished as a result of the selected fuel cycle. This change makes the criterion more understandable and operational by stating that the quotient of the rate of fuel consumption by the rate of fuel supply is what is being evaluated.

The criterion *Feasibility* was changed to *Technical Feasibility* and its definition was altered to: The risk associated with choosing a fuel cycle that requires technology that has not yet been developed, thus preventing the fuel cycle's implementation immediately or in the near-future. This change makes the definition less ambiguous, more understandable, and much more operational as to how feasibility will be evaluated. With these changes the risks hierarchy was completed. The finalized hierarchy can be seen below in Table VI

VII. NEW HIERARCHY TESTING

In order to evaluate the effectiveness of the new hierarchy and the new definitions, a series of surveys were constructed electronically to perform the same pair-wise comparisons that were performed at the conference. However, these surveys were targeted at members of the general public, as a worst-case test, under the assumption that members of the general public would naturally have the highest inconsistency given their relative unfamiliarity with the nuclear fuel cycle. The results of the sample size versus the inconsistency threshold can be seen in Table VII.

VIII. DISCUSSION

The rate of reduction, that is the percentage of respondents who fail to meet the 10% inconsistency threshold, in the sample size is essentially the same for the electronically conducted surveys and for the surveys conducted at the large nuclear engineering and science conference. However, because the electronically conducted surveys were performed on members of the general public, whereas the previous surveys were conducted on nuclear engineers and scientists, it is the opinion of the authors that the new hierarchies represent a substantial improvement in evaluating the important aspects of selecting a nuclear fuel cycle. That a large number of members of the general public still remain, about 40%, after the relatively difficult 10% inconsistency threshold, can be viewed as a success in terms of refining nuclear fuel cycle criteria to a point where members of the general public understand the relevant aspects, without diluting the meaning of the terms.

IX. FURTHER WORK

The new hierarchies will be utilized to conduct similar surveys on members of the following expert groups: Economists, Environmental Scientists, Nuclear Engineers & Scientist, and Political Scientists. With the data derived from these surveys, the proper weighting of the criteria can

Benefits	Costs	Opportunities	Risks
Disposal Flexibility	Facility Construction, Operation, & Maintenance	American Economic Development	Accidents or Nuclear Material Release
Fuel Requirement Reduction	Legal Fees & Fines	Energy Policy Leadership	Potential Future Burden
Increase Technical Workforce	Licensing	Long-term Electricity Production	Proliferation Potential
Legal Resolution	Proliferation Prevention	New Technology Development	Public or Political Rejection
Local Economic Development	Supplemental Infrastructure Development	Nuclear Industry Growth	Radiation Exposure
National Infrastructure Development	Switching Policy	U.S. Government Competence	Supply Availability
Public & Political Acceptance	Transportation		Technical Feasibility

Table VI. Final Criteria Hierarchies

	Sample Size				
Hierarchy	No Threshold	20% Inconsistency	15% Inconsistency	10% Inconsistency	Percent Reduction
Benefits	87	55	46	34	61%
Costs	70	44	37	25	64%
Opportunities	86	60	47	38	56%
Risks	84	55	42	33	61%
Total	327	214	172	130	60%

Table VII. Sample Sizes of Surveys Collected from the General Public for New Hierarchy

be given. For the final evaluation of the fuel cycle alternatives against the metrics, a consensus from the relevant expert groups will be needed. A final comparison of fuel cycles will be presented based on their evaluations against each metric for each criteria.

X. CONCLUSION

Through understanding the important aspects of a nuclear fuel cycle from multiple perspectives, solutions that are better aligned with the interests of the general public should arise. This research has laid groundwork on how to evaluate what is important and how to express those in understandable and unambiguous terminology. Understanding what is important to the general public and addressing their concerns about nuclear waste cannot be overemphasized if nuclear power is ever to experience another renaissance.

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