Quantifying Public Perceptions on the Nuclear Fuel Cycle – 15395

John M. Swanson*, Sama Bilbao y León, and Ishoc Salaam
*Virginia Commonwealth University, swansonjm@vcu.edu

ABSTRACT

The nuclear fuel cycle in the United States, specifically the back end portion, remains an unresolved and persistent issue. In comparison with the technical aspects of many different fuel cycles, less attention has been given to public perceptions and attitudes toward certain alternatives. Understanding what the general public values in terms of a nuclear fuel cycle will assist in selecting a nuclear fuel cycle that optimizes the balance between technical feasibility and public acceptance. A multi-criteria decision analysis (MCDA) model was created to incorporate the general public's perceptions on qualified individuals and on important technical and non-technical aspects of any general fuel cycle. Analyzing the pair-wise comparisons for each criterion through the Analytic Hierarchy Process (AHP) yielded the relative importance of each aspect. A major finding is that the general public tend to view environmental scientists as qualified as nuclear engineers and scientists in selecting a method of used nuclear fuel disposal for the United States.

INTRODUCTION

The enduring issue of used nuclear fuel disposal continues to stain the reputation of the United States in terms of its energy policy. In order to resolve this issue, numerous studies have been completed, reports have been written, and commissions have been formed and yet, despite the tremendous effort, used nuclear fuel continues to be parked in dry casks at nuclear power plants with no clear time table on its final removal and deposition [1]. Although many of these reports and studies have focused on technological challenges associated with used nuclear fuel disposal, comparatively less attention has been given toward the public perception and acceptance of a nuclear fuel cycle [2] [3] [4] [5]. There are many technical problems to be solved within many nuclear fuel cycles and research in these fields represent valuable advances; however, failure to factor in public perceptions can obstruct or defeat even the most technically viable plans [6]. This can clearly be seen in the case of the United States' planned geological repository in Yucca Mountain, Nevada which has been plagued with legal resistance, political dissonance, and localized opposition [1].

It is clear that if a fuel cycle's implementation is to be successful it must be both technically feasible and publicly acceptable. Evaluating multiple decision alternatives, such as the various options for the fuel cycle, on multiple disparate factors, such as uranium utilization and public acceptance, and combining them into a shared value space is the goal of many techniques in the field of mulit-criteria decision analysis (MCDA). One of the first steps in utilizing these techniques is to evaluate the relative importance of the multiple different criteria. Understanding what criteria the general public view as important and by approximately how much can help effectively utilize resources in the implementation of a nuclear fuel cycle.

DEVELOPMENT

A methodology similar to that of Yi et al. was followed in terms of surveying for MCDA and establishing hierarchies [7]. The potential areas in which criteria could exist were defined as benefits, costs, opportunities, and risks, also known as BOCR.

Development of Criteria

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 South Atlantic university. A final step in generating the initial criteria was brainstorming between members of the research group. These criteria were taken to large nuclear engineering and science conference and further evaluated by attendees. It became evident that the criteria needed to be revised for improved clarity, understandability, comprehensiveness, and mutual exclusivity. The criteria were reevaluated with the help of two outside nuclear scientists and two outside environmental scientists. After a final revision the following criteria were decided upon and grouped into the BOCR hierarchy shown below in Figure 1.

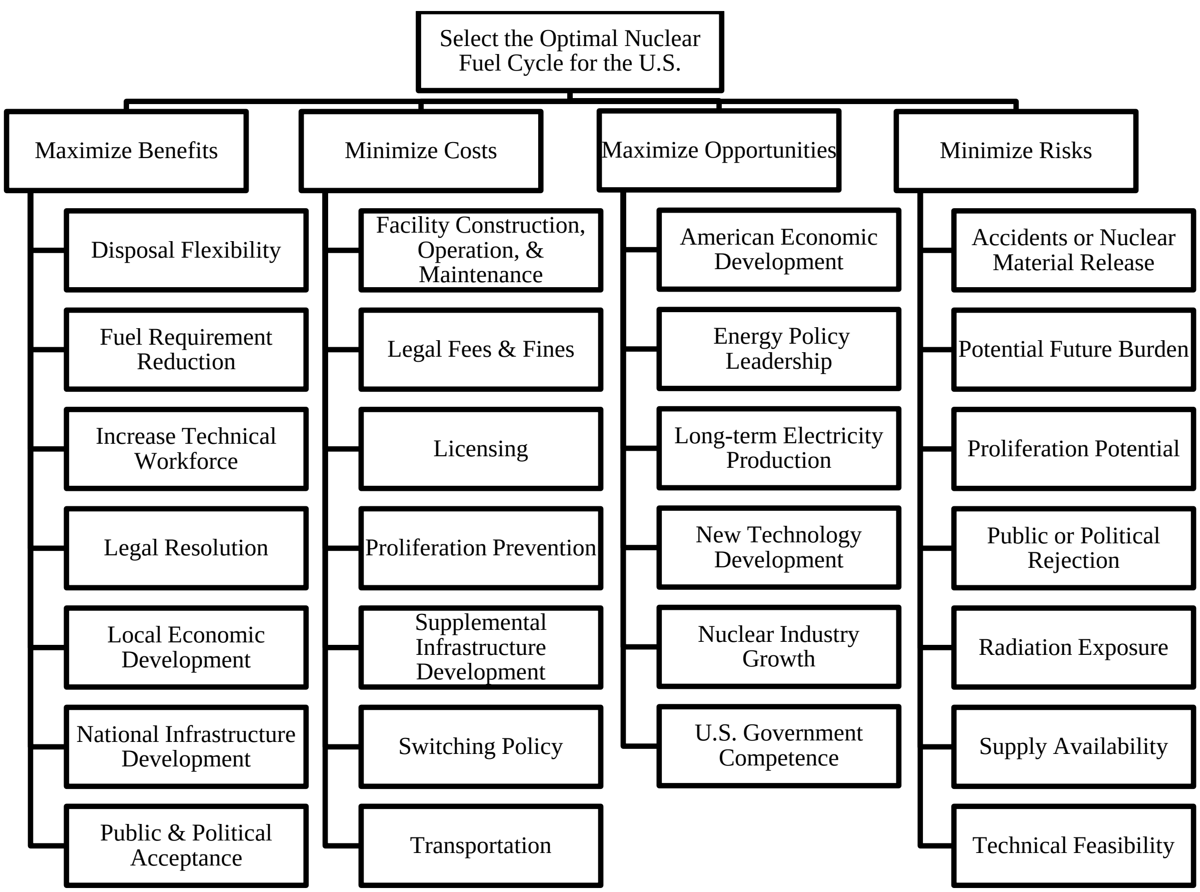

Fig. 1. Finalized Hierarchy and Criteria

Criteria Definitions

Under *Benefits*: The definition of *Disposal Flexibility* is given as*:* 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 definition of *Fuel Requirement Reduction* is given as: The benefits of selecting a fuel cycle that reduces the need to mine or import additional nuclear fuel (i.e. uranium). The definition of *Increase Technical Workforce* is given as: The benefits of choosing a fuel cycle that promotes the training of more high-paid engineers, scientists, and technical professionals. The definition of *Legal Resolution* is given as: 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. The definition of *Local Economic Development* is given as: 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.). The definition of *National Infrastructure Development* is given as: The benefits gained from the development of national infrastructure (i.e. interstate highways, railways, and support facilities) in connection with a selected fuel cycle. Finally, the definition of *Public & Political Acceptance* is given as: 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.

Under *Costs*: The definition of *Facility Construction, Operation, & Maintenance* is given by: The costs associated with the construction, operation and maintenance of any required facility (repository, reprocessing facility, etc.) for a selected fuel cycle. The definition of *Legal Fees & Fines* is given by: 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. The definition of *Licensing* is given as: The costs associated with the licensing of facilities, related technologies, and methods for a selected fuel cycle. The definition of *Proliferation Prevention* is given as: 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). The definition of *Supplemental Infrastructure Development* is given as: The costs of developing the additional infrastructure (i.e. interstate highways, railways, and technical workforce) required for a selected fuel cycle. The definition of *Switching Policy* is given as: The costs of switching from the currently selected fuel cycle to an alternative fuel cycle (i.e. workforce retooling, legislation, sunk costs). Finally, the definition of *Transportation* was given as: The costs of the transportation of the used fuel in a selected fuel cycle (trucks, drivers, barges, trains, etc.).

Under *Opportunities:* The definition of *American Economic Development* is given as: The opportunity of selecting a fuel cycle that stimulates the national economy due to job creation and tax revenue. The definition of *Energy Policy Leadership* is given as: 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. The definition of *Long-term Electricity Production* is given as: 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 definition of *New Technology Development* is given as: 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. The definition of *Nuclear Industry Growth* is given as: 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. Finally, the definition of *U.S. Government Competence* is given as: 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.

Under *Risks*: The definition of *Accidents or Nuclear Material Release* is given as: 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. The definition of *Potential Future Burden* is given as: 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. The definition of *Proliferation Potential* is given as: The risk of selecting a fuel cycle that has greater potential of having nuclear materials diverted for non-authorized applications (i.e. weapons). The definition of *Public or Political Rejection* is given as: 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 definition of *Radiation Exposure* is given as: 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. The definition of *Supply Availability* is given as: The risk of the fuel inventory being consumed faster than it can be replenished as a result of the selected fuel cycle. Finally, the definition of *Technical Feasibility* is given by: 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.

Analytic Hierarchy Process

The MCDA technique that was utilized to evaluate the criteria in a meaningful way is known as the Analytic Hierarchy Process (AHP). AHP, as first developed by Thomas Saaty in 1980, utilizes hierarchies, pair-wise comparisons, and consistency analysis to obtain weights for decision alternatives [8]. 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 sub-criteria 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 [8]. 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 criteria 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 [6]. Thus each criterion 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 defined as follows:

$$CI = \frac{\lambda_{max} - n}{n - 1} \qquad \text{(Eq. 1)}$$

Where λ_{max} is the maximum eigenvalue of the judgment matrix and n is the order of the matrix. 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). The random index is the average consistency index for a large number of randomly assigned judgment matrices [8]. For decisions with more than three criteria a consistency ratio less than 10% is recommended by Saaty [8]. To develop the overall weights, or priorities, of the criteria, the judgment matrix is normalized and each row averaged.

Subject Matter Experts

It was predicted that simply using the derived priorities that are developed from the general public about the different aspects of the nuclear fuel cycle would not yield a good indication of what is actually feasible since the general public is not very familiar with many of the concepts presented. Because of this, a strategy was devised that in addition to having members of the general public evaluate the aspects previously mentioned they would also evaluate the qualifications of relevant subject matter experts. The relevant subject matter experts were *Economists, Environmental Scientists, Nuclear Engineers & Scientists,* and *Political Scientists.* Additionally, the general public would evaluate their own qualifications against the previously mentioned subject matter experts to derive a weighting of their own priorities. From these comparisons each group of subject matter experts will have their priorities weighted by how the general public views them as qualified, although the actual elicitations from subject matter experts has not yet be completed at the writing of this paper.

EVALUATION

With the criteria finalized and an evaluation methodology in place, five electronic surveys were constructed, one comparing the subject matter experts, and one for each of the branches of the decision hierarchy: benefits, costs, opportunities, and risks. The surveys followed the following format: After a brief introduction explaining that we will be choosing “the best method to dispose of used nuclear fuel in the long term,” a question was posed to rank, one through five, the relevant subject matter experts in terms of who is most qualified “in terms of selecting a method of used nuclear fuel disposal for the United States.” Similarly, in the other four BOCR surveys a question was posed, after the introduction, to rank the criteria, one through six or seven, by the most important. For example for the benefits survey read as follows: “Please rank the following criteria from the most important (1) to the least important (7) in terms of the BENEFITS that can be derived from the selection of a given method for the disposal of used nuclear fuel in the US.” The definitions of each of the concepts were included. These rankings were done first in an effort to improve consistency amongst respondents since it allows respondents to become familiar with the different concepts, to feel comfortable with ranking them, and give the respondents something to fall back on when it came to the pair-wise comparisons [8].

After the ranking of either subject matter experts or decision criteria, the respondents were asked to perform the pair-wise comparisons for each possible combination. The number of pair-wise comparisons, N, is related to the number of objects being evaluated, m, by equation 2:

$$N = \frac{m(m-1)}{2} \qquad \text{(Eq. 2)}$$

Thus for the subject matter experts survey, *m* is five and the number of pair-wise comparisons is only ten. Likewise, for the opportunities survey, *m* is six and the number of pair-wise comparisons is 15. For the other three surveys, *m* is seven and the number of pair-wise comparisons is 21 each. For each pair-wise comparison, respondents were asked two questions, the first being to select which subject matter expert is more qualified, or criterion is more important, and the second question asking how much more. Examples of these can be seen below in TABLE I and II.

TABLE I. Example of pair-wise comparisons for subject matter experts

A	B	Which one is more qualified?	How much more qualified?
Economists	Political Scientists	Equal	N/A
Environmental Scientists	Nuclear Engineers & Scientists	B	Slightly

TABLE II. Example of pair-wise comparisons for decision criteria

A	B	Which one is more important?	How much more important?
Legal Resolution	Public & Political Acceptance	B	Moderately
Disposal Flexibility	Increase Technical Workforce	A	Strongly

The possible responses for the magnitude of importance are limited to the qualitative terms, *equal*, *slightly*, *moderately*, *strongly*, *very strongly*, and *extremely*, this was done since qualitative terms are more familiar to individuals who are not mathematically inclined, as is expected to be the majority in the general public [8]. These qualitative terms were then interpreted into quantitative terms by applying an appropriate scale. The details of this are in the following section titled INTERPRETATION.

Special care was given to achieve nationally representative demographics and there were no anomalous findings with the demographic data, and they will not be discussed further. The sample sizes can be seen below in TABLE III. 100 responses were ordered for each group; however, because of the tedious nature of pair-wise comparisons only the survey on subject matter experts was completed as ordered. This is because the remaining four surveys unfortunately had fairly high abandonment rates, i.e. when a respondent starts the survey and then quits before completion.

TABLE III. Survey sample sizes

Survey Description	Subject Matter Experts	Benefits	Costs	Opportunities	Risks	Total
Sample Size	100	87	70	86	84	427

INTERPRETATION

With the surveys completed the qualitative data was interpreted through applying a numerical scale to the terms. Because there is uncertainty involving interpretation, three different scales were utilized to make the results more robust. These scales are known as the integer, balanced, and power scales respectively and the numerical interpretations are shown below in TABLE IV and visually in Figure 2.

For the non-integer scales the values are generated by equations 3 and 4 for the balanced and power scales respectively [9].

$$x_b = \frac{w}{1-w} \qquad \text{(Eq. 3)}$$

$$x_p = \left(\sqrt[\gamma-1]{9}\right)^L \qquad \text{(Eq. 4)}$$

Where for the balanced scale the values of *w* are chosen to be 0.5, 0.55, 0.6, 0.65, …, 0.9. For the power scale, γ is the number of increments of judgment used for comparing attributes, for which 9 was used, and *L* is an integer from 0 to γ-1 [9].

TABLE IV. Numerical interpretation scales

Intensity of Importance			
Integer	Balanced	Power	Explanation
1	1	1	Equal
2	1.22	1.32	Slightly
3	1.50	1.73	Moderately
4	1.86	2.28	
5	2.33	3	Strongly
6	3	3.95	
7	4	5.20	Very Strongly
8	5.67	6.84	
9	9	9	Extremely

A code was developed and AHP was performed on each survey respondent using each numerical interpretation scale. To arrive at a set of group priorities the respondent’s evaluations were aggregated into a group decision matrix. This was achieved by taking the geometric mean of each decision matrix element across all respondents, and then performing AHP on that decision matrix [8]. The consistency was evaluated under each for the individual respondents and for the resulting group matrix. In addition to evaluating the respondent with no inconsistency threshold, three thresholds were utilized, 20%, 15%, and 10%. According to Saaty, an inconsistency less than 10% represents an acceptable level of randomness in these elicitations, and this is taken as our most extreme threshold [8]. Under these threshold scenarios, if the inconsistency of the respondent’s derived priorities was higher than the threshold the respondent would be removed from the evaluation of the group matrix.

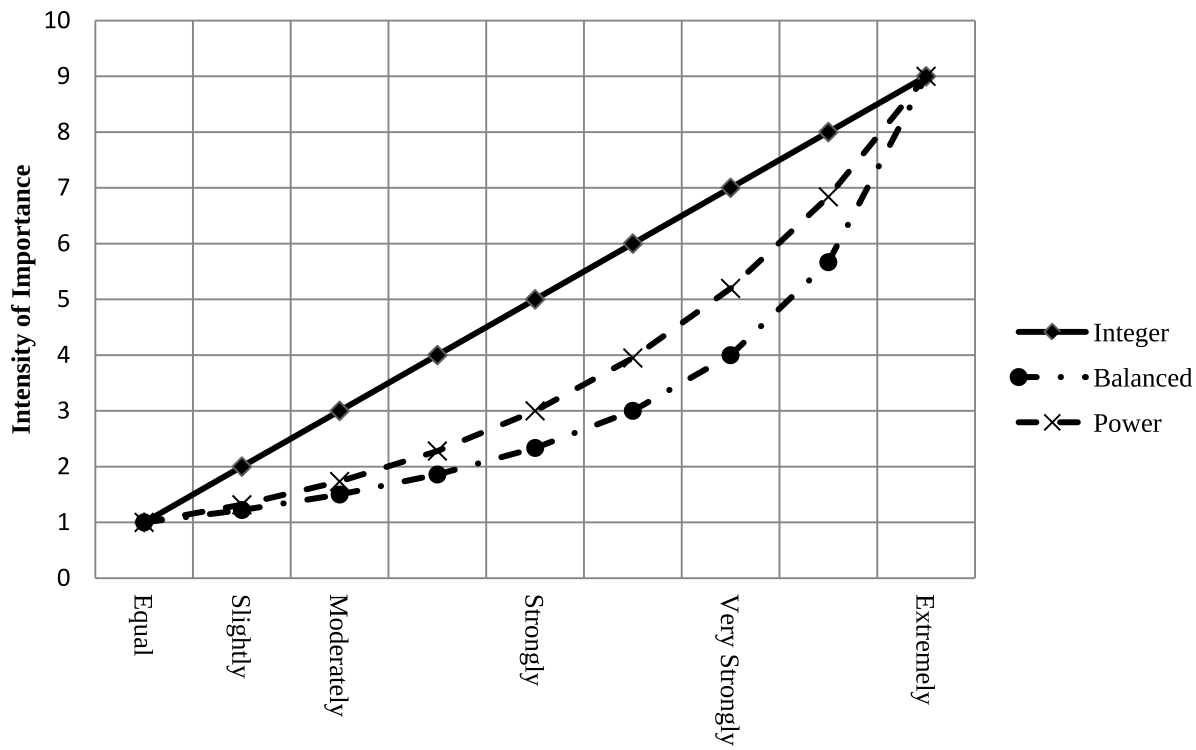

Fig. 2. Numerical Interpretation Schemes

RESULTS

Since applying the inconsistency thresholds did not have a significant effect of the derived priorities, only the subject matter expert result is shown for illustration and this can be seen in Figure 3. The derived priorities of each subject matter expert can be seen in Figure 4. The derived priorities of the BOCR criteria can be seen in Figures 5 through 8. The effects of applying the inconsistency thresholds on the sample size using an integer interpretation scheme can be seen below in TABLE V. Similar trends occurred with the use of balanced or power scales.

TABLE V. Effect of inconsistency thresholds on sample size using integer scale

	Threshold				
Survey Type	None	20%	15%	10%	Percent Reduction
Experts	100	82	74	54	46%
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	427	296	246	184	57%

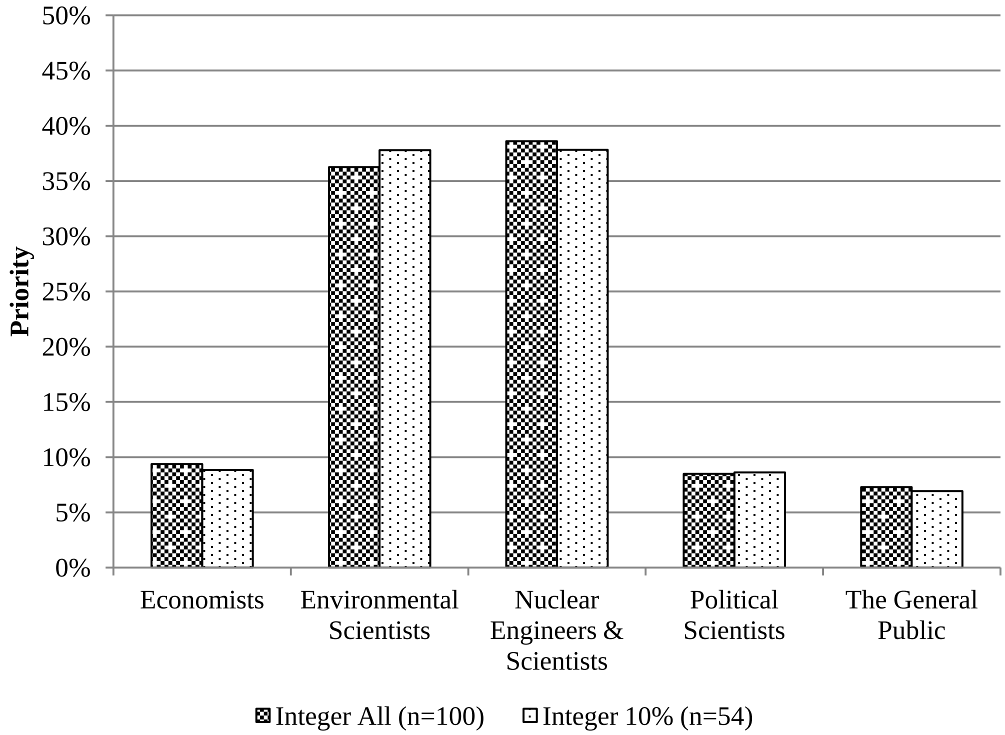

Fig. 3. Priority Change of Subject Matter Experts

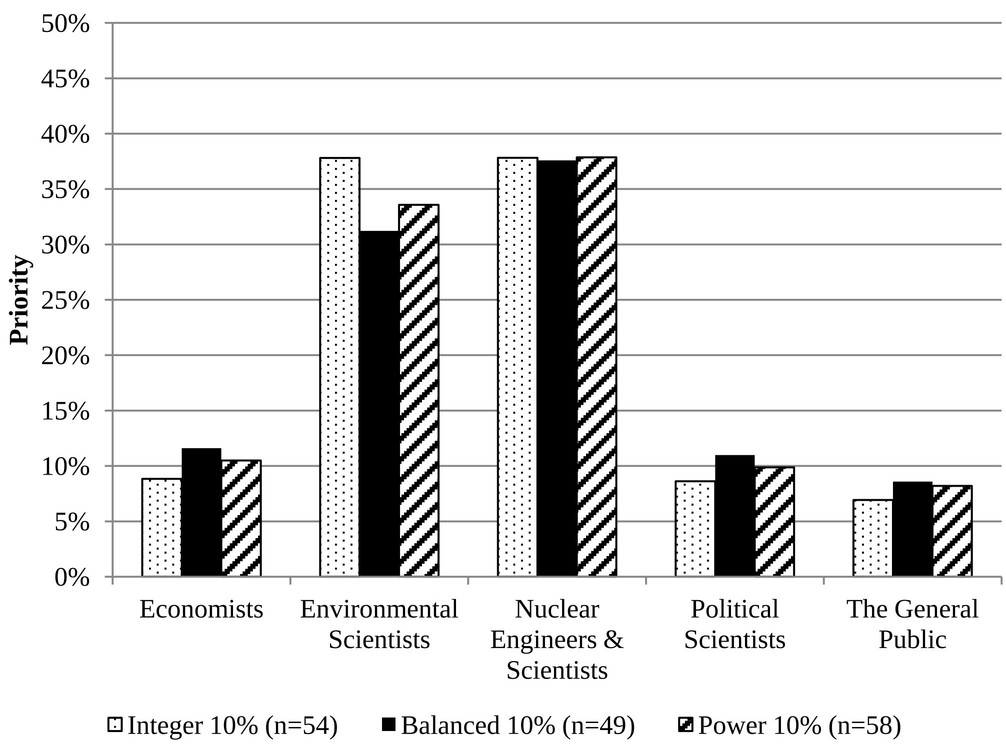

Fig. 4. Priority of Subject Matter Experts

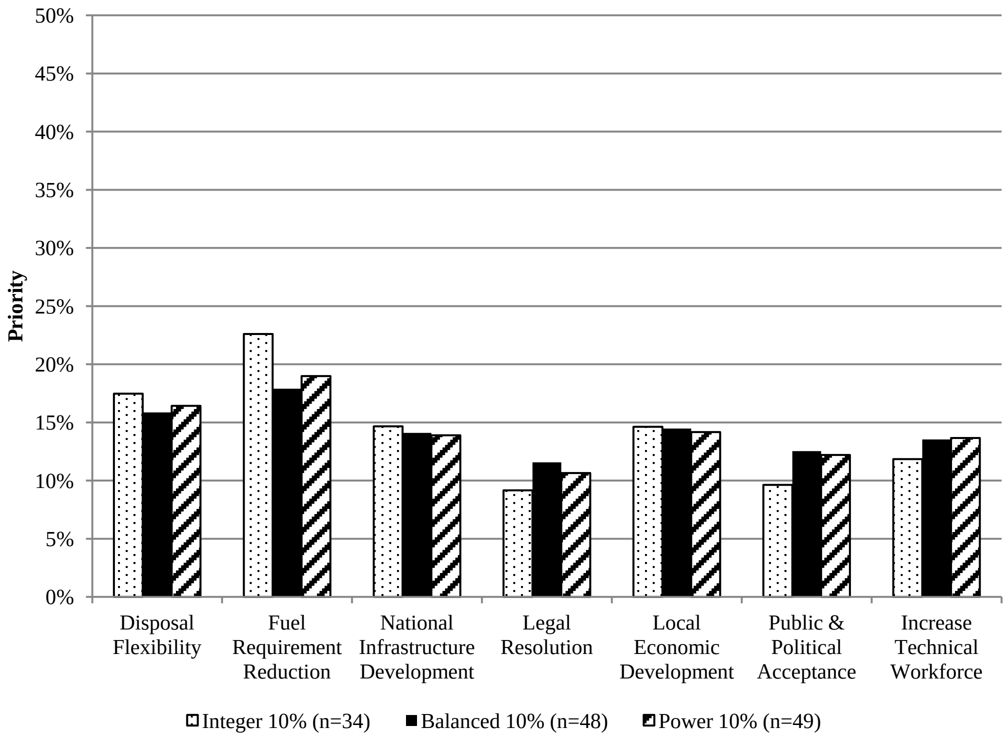

Fig. 5. Priority of Benefits Criteria

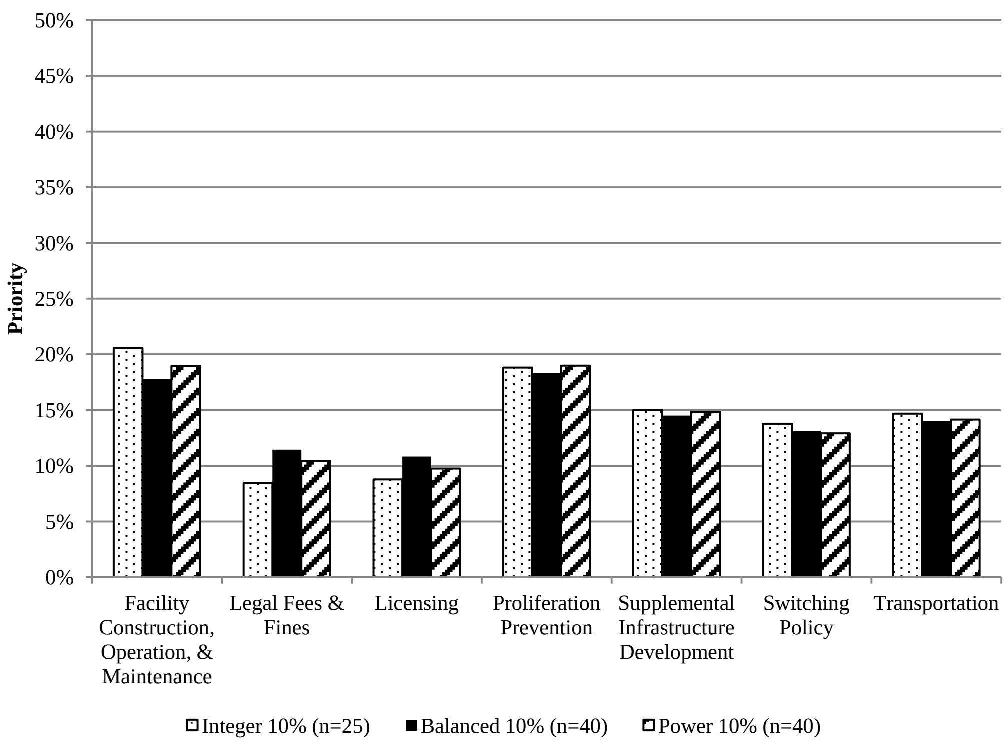

Fig. 6. Priority of Costs Criteria

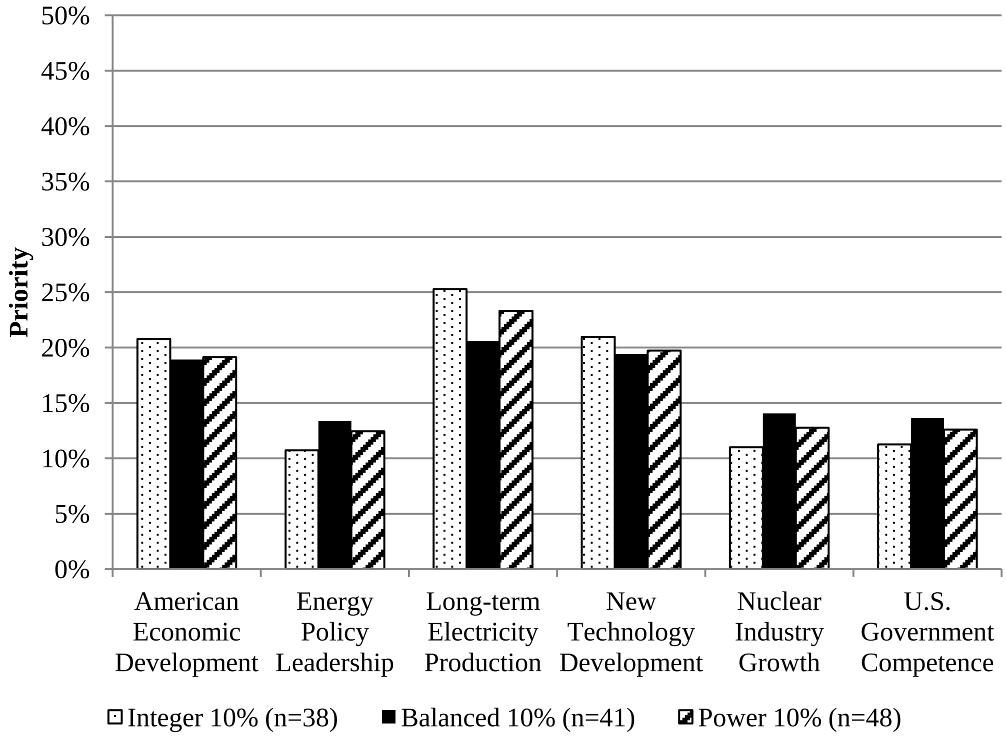

Fig. 7. Priority of Opportunities Criteria

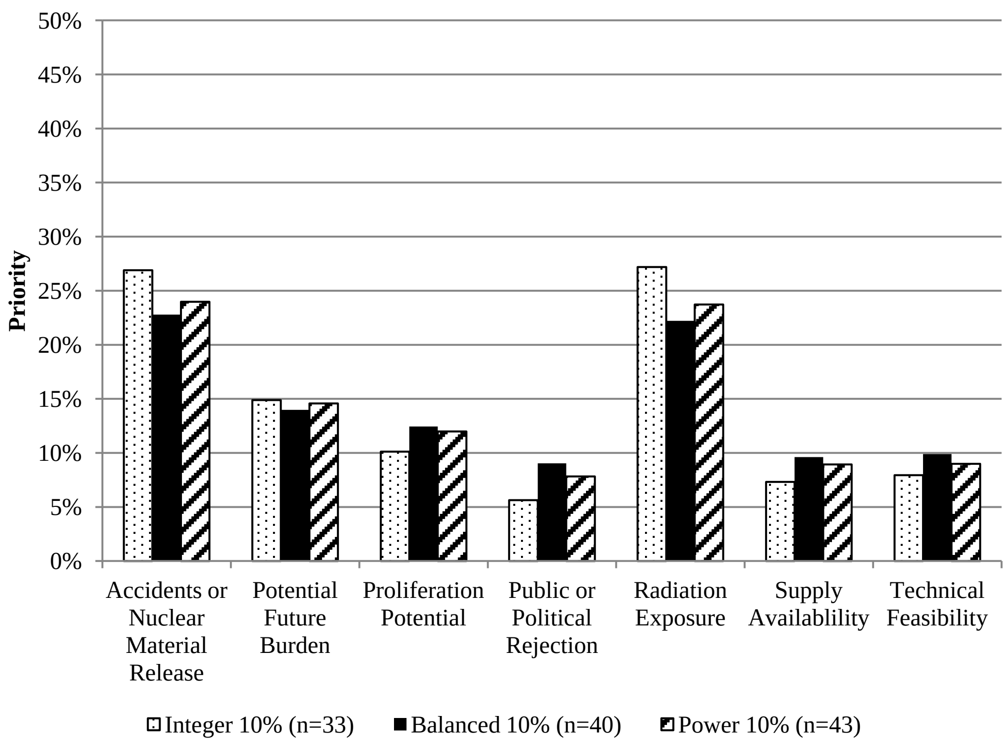

Fig. 8. Priority of Risks Criteria

DISCUSSION

Applying the inconsistency thresholds showed a clear reduction in the sample size, usually accounting for the removal of about 60% of the total responses. Although it would always be better to lower the percentage of inconsistent responses, it is shown in Figure 3 that the inclusion of the inconsistent respondents did not have appreciable effects on the final derived priorities. The fact 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.

The derived priorities of the subject matter experts, as shown in Figure 4, present a very interesting and important finding, namely that from the general public's point of view nuclear engineers and scientists are essentially equally as qualified as environmental scientists in selecting a method for used nuclear fuel disposal. Additionally, economists, political scientists, and even the general public themselves are all nearly equally unqualified. This finding should be incorporated in any strategy aimed at communicating used nuclear fuel disposal to the general public. Specifically, environmental scientists need to be represented nearly equally alongside nuclear engineers and scientists.

Within the derived priorities of the benefits criteria, as shown in Figure 5, there is no clear winner. However, *Fuel Requirement Reduction* does score highest implying that the general public views effective resources utilization as an important aspect. This too should be incorporated into any communications campaign aimed at the general public about used nuclear fuel disposal.

The derived priorities of the costs criteria, as shown in Figure 6, show that the most important aspects are *Facility Construction, Operation, & Maintenance* and *Proliferation Prevention.* The first important aspect implies that the general public does have a sense of the costs of building these major facilities that would be involved in resolving the nuclear fuel cycle and that minimizing these costs is important to them. Additionally, the cost of *Proliferation Prevention* scores relatively high suggesting that an effective utilization of resources spent toward this attribute is essential. Interestingly, the costs of *Licensing* and *Legal Fees & Fines* scored lowest indicating that the general public may not have an understanding of these concepts as the pertain to the current nuclear fuel cycle and that understanding these concepts may lie outside the realm of a simple explanation. Effectively communicating the costs of a used nuclear fuel should probably address *Facility Construction, Operation, & Maintenance* and *Proliferation Prevention* without spending significant time on the costs of *Licensing* or *Legal Fees & Fines*.

The opportunities criteria priorities, as shown in Figure 7, demonstrate that the three most important aspects of this section are *Long-term Electricity Production*, *New Technology Development,* and *American Economic Development*. This shows that the general public value sustainability but not independent of developing new technology or developing the American economy. When communicating a strategy of used nuclear fuel disposal these aspects should be clearly highlighted and emphasized.

The derived priorities of the risks criteria, as shown in Figure 8, present a challenging hurdle in communications strategies. Specifically, the most important aspects to the risks of a nuclear fuel cycle are *Radiation Exposure* and *Accidents or Nuclear Material Release* and they are much more important relative to their fellow risk criteria. Although this can be viewed as irrational given the copious amount of regulations and safeguards in the nuclear industry already in place, it nonetheless cannot be ignored. An effective communications strategy about used nuclear fuel disposal must address the topics of potential accidents and radiation exposure.

FUTURE WORK

These findings will be used to populate one aspect of a larger decision making model, with the ultimate goal of selecting a nuclear fuel cycle for the United States that is both technically feasible and publically acceptable. Additionally, a multi-item scale will be utilized to understand the different aspects of qualifications for the subject matter experts.

CONCLUSION

Members of the general public were surveyed with the goal of understanding their views on the importance of different benefit, cost, opportunity, and risk aspects and the qualifications of different subject matter experts as they pertain to used nuclear fuel disposal. The Analytic Hierarchy Process was utilized to synthesize the data into priorities that represent the overall group's values. A large number of respondents were removed by applying an inconsistency threshold of 10%, but this did not result in significant changes in the final priorities for each group. A major finding is that nuclear engineers and scientists are viewed by the general public as essentially equal to environmental scientists in their qualifications for selecting a method for used nuclear fuel disposal. This research begets the following recommended strategy for communicating to the general public about used nuclear fuel disposal: Represent nuclear engineers and scientists equally alongside environmental scientists while emphasizing the benefits of reducing fuel usage, the opportunities of having long-term electricity production, developing new technology, and growing the American economy that could result from the implementation of a nuclear fuel cycle. Additionally, care must be used in addressing the costs of building any new facility and insuring counter-proliferation costs are utilized effectively. Finally, the issue of radiation exposure and potential accidents must be addressed if there is a hope for the general public to be accepting. With environmental scientists corroborating nuclear engineers and scientists, the communication of all of these topics should be much more effective.

REFERENCES

1. "Blue Ribbon Commission on America's Nuclear Future. Report to the Secretary of Energy," Tech. rep., Blue Ribbon Commission on America's Nuclear Future (2012).
2. P. O. KIM, K. J. LEE, and B. W. LEE, "Selection of an Optimal Nuclear Fuel Cycle Scenario by Goal Programming and the Analytic Hierarchy Process," *Annals of Nuclear Energy*, **26**, 5, 449 – 60 (1999).
3. M. MERKHOFER and R. KEENEY, "A Multiattribute Utility Analysis of Alternative Sites for the Disposal of Nuclear Waste," *Risk Analysis*, **7**, 2, 173 – 194 (1987).
4. R. L. KEENEY and G. A. ROBILLIARD, "Assessing and Evaluating Environmental Impacts at Proposed Nuclear Power Plant Sites," *Journal of Environmental Economics and Management*, **4**, 2, 153 – 166 (1977).

5. S. RASHAD and F. HAMMAD, “Nuclear power and the environment: comparative assessment of environmental and health impacts of electricity-generating systems,” *Applied Energy*, **65**, 1-4, 211 – 229 (2000).
6. C. R. SUNSTEIN, “Probability Neglect: Emotions, Worst Cases, and Law,” *John M. Olin Law & Economics Working Paper*, **138**, 1, 1–35 (2001).
7. S.K. YI, H.Y. SIN, and E. HEO, “Selecting Sustainable Renewable Energy Source for Energy Assistance to North Korea,” *Renewable and Sustainable Energy Reviews*, **15**, 1, 554–63 (2011).
8. T. L. SAATY, *Decision Making for Leaders*, RWS Publications, Pittsburgh, Pennsylvania (2008).
9. M. A. ELLIOTT, “Selecting Numerical Scales for Pair-wise Comparisons,” *Reliability Engineering and System Safety*, **95**, 7, 750 – 763 (2010).

ACKNOWLEDGEMENTS

This material is based upon work supported by the Department of Energy Nuclear Energy University Program (DOE NEUP) grant 12-3391.