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INCORPORATING PUBLIC PERCEPTIONS INTO THE SELECTION OF A NUCLEAR FUEL CYCLE

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INCORPORATING PUBLIC PERCEPTIONS INTO THE SELECTION OF A
NUCLEAR FUEL CYCLE

A thesis submitted in partial fulfillment of the requirements for the degree of
Master of Science in Mechanical & Nuclear Engineering at
Virginia Commonwealth University.

by

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B.S. Mechanical Engineering - Virginia Commonwealth University - 2013

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To Iswarya: Thank you for being you.

Finally, to the reader, by spending the time to read through the acknowledgements you hopefully have a better understanding of the author of this thesis. I will
close with a quote that has resonated with me from the 14th Dalai Lama about the purpose of all this education.

“One problem with our current society is that we have an attitude towards education as if it is there to simply make you more clever, make you more ingenious. Sometimes it even seems as if those who are not highly educated, those who are less sophisticated in terms of their educational training, are more innocent and more honest. Even though our society does not emphasize this, the most important use of knowledge and education is to help us understand the importance of engaging in more wholesome actions and bringing about discipline within our minds. The proper utilization of our intelligence and knowledge is to effect changes from within to develop a good heart.”

- The 14th Dalai Lama, The Art of Happiness
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Abstract

INCORPORATING PUBLIC PERCEPTIONS INTO THE SELECTION OF A NUCLEAR FUEL CYCLE

By John Michael Swanson

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Mechanical & Nuclear Engineering at Virginia Commonwealth University.

Virginia Commonwealth University, 2015.

Director: Sama Bilbao y León,
Associate Professor and Director of Nuclear Engineering Programs,
Department of Mechanical & Nuclear Engineering

The final disposal location for used nuclear fuel in the U.S. remains unresolved. A major complication in resolving this issue has historically been the lack of public acceptance. This motivates the creation of a decision making model for selecting a nuclear fuel cycle in the U.S. that incorporates the preferences of the public. A model based on the Analytic Hierarchy Process (AHP) was created, tested, and shown to be problematic in incorporating public opinion into decision objectives. A new model based on Multi-Attribute Utility Theory (MAUT) has been created. This model contains the fundamental objectives for both technical and non-technical factors in both the short and long term for the decision. Additionally, the relevant subject matter experts involved in a nuclear fuel cycle selection are evaluated based on the public’s perception of their qualifications, and environmental scientists are found to be considered equally as qualified as nuclear engineers and scientists.
CHAPTER 1

INTRODUCTION

1.1 Research Context

This work represents one component of a larger research project aimed at ‘re-branding’ the nuclear fuel cycle. The goal of the larger research project is aimed at creating an effective communication strategy that conveys the nuclear fuel cycle as “a familiar and low-risk concept whose contribution to people’s everyday life is perceived as a positive.” The objective of this work is the creation of a decision making model that can be utilized by policy makers to ultimately help incorporate public perceptions into the selection of a nuclear fuel cycle.

1.2 Background Material

The following section and its subsections have been included to give the reader a basic understanding of concepts pertaining to nuclear energy, the nuclear fuel cycle, and the historical background of nuclear waste disposal.

1.2.1 Nuclear Energy

Energy can be derived from many sources; from the chemical combustion of hydrocarbons, from the force of the wind, and from the changing of the nuclear properties of atoms to name but a few. Of interest within this research is the energy derived by nuclear means. There exist two primary types of nuclear reactions that are used to produce energy. The first of these is known as fusion and it involves the combining of two light nuclei into one heavier nucleus, and in the process releasing
energy. The second of these is fission and it involves the splitting of one very heavy nucleus into two or more lighter nuclei, and also in the process releasing energy. An incident neutron, with enough energy, impacting the very heavy nucleus is often required to induce a fission reaction. In terms of generating electricity from nuclear reactions, the only method that is currently in use is fission. The primary fuel in use for this type of electricity production is uranium (U).

In nature, uranium consists of two isotopes, i.e., two versions of the same element with the same chemical properties but with a different number of neutrons and thus different atomic weights. The majority of uranium that is found in nature is $^{238}\text{U}$, accounting for 99.3%. The balance, i.e., 0.7%, of natural uranium is $^{235}\text{U}$. $^{238}\text{U}$ is composed of 92 protons and 146 neutrons; the sum of which yields 238. $^{235}\text{U}$ is similarly composed of 92 protons, but instead only has 143 neutrons; the sum of which yields 235. Both $^{238}\text{U}$ and $^{235}\text{U}$ can potentially be fissioned to produce energy; however, $^{235}\text{U}$ can be efficiently fissioned with incident neutrons of very low energy while $^{238}\text{U}$ can primarily be fissioned only with higher energy neutrons. The vast majority of nuclear reactors around the world operate with lower energy neutrons and thus have $^{235}\text{U}$ as their primary fuel; however, in order for the $^{235}\text{U}$ to produce electricity economically, the concentration of $^{235}\text{U}$ needs to be increased from 0.7% to around 3 to 4%. It is the life cycle of this uranium fuel that is of prime importance to our current research and it is known as the nuclear fuel cycle.

1.2.2 The Nuclear Fuel Cycle

The nuclear fuel cycle covers the entire life of nuclear material that is used for fuel in reactors to produce electricity. A simple schematic of a nuclear fuel cycle is included in Figure 1. The nuclear fuel cycle begins with mining the nuclear material ore, i.e., primarily uranium, out of the ground through one of three methods: open
pit mining, underground mining, or solution based mining, also known as *in-situ* leaching [1]. After the uranium ore is mined it must be milled and concentrated into a form that is suitable for transportation and handling. Thus the uranium ore is converted into $\text{U}_3\text{O}_8$, what is known as yellow cake uranium [1]. As mined uranium will only contain around 0.7% of readily usable nuclear material, i.e., fissionable $^{235}\text{U}$, the uranium needs to be enriched to contain around 3 to 4% so it can be effectively used in existing nuclear power plants [1]. To enrich the uranium, it is first converted from $\text{U}_3\text{O}_8$ into $\text{UF}_6$, which is known as uranium hexafluoride. This conversion is done because the enrichment stage requires uranium in a gaseous form and uranium hexafluoride, although a solid at room temperature, becomes as gas
at 56°C (133°F) [1]. The enrichment process involves separating the UF$_6$ that has the $^{235}$U bonded to six fluorine atoms from the UF$_6$ that has the $^{238}$U bonded to six fluorine atoms. This separation is possible based on the difference in the atomic weight of the two molecules since $^{235}$U has three less neutrons and is thus lighter. The primary method for achieving this enrichment step is through using centrifuges to separate the molecules. Once the uranium has been enriched to around 3 to 4% it is chemically converted once more; this time into a ceramic form known as uranium dioxide (UO$_2$) [1]. The ceramic uranium dioxide is then formed into small pellets, which are stacked on top of each other and placed into long rods, forming fuel rods [1]. These fuel rods are then assembled into square bundles [1]. These fuel bundles are then emplaced in nuclear power plant reactors; then the fission reactions are initiated, energy is generated, and electricity is produced.

Eventually, after most of the $^{235}$U has been fissioned, the nuclear reactor will need fresh fuel to sustain its operation. The used nuclear fuel is then removed from the reactor; however, the used nuclear fuel is still radioactive and generates heat, albeit at a decreasing rate. Thus the used fuel must be handled accordingly. Typically, the used fuel is first placed in deep pools of water where it cools for a period of several months to several years [1]. After it has cooled sufficiently enough, the used fuel can undergo one or more of the following processes to complete the nuclear fuel cycle:

- The used nuclear fuel can be put in large concrete dry casks that cool naturally by air outside of nuclear power plants.

- The used nuclear fuel can be collected and disposed of underground in a deep geological repository.

- The used nuclear fuel can be reprocessed and a portion recycled for use again in a nuclear reactors while the rest is disposed of underground in a deep geological
1.2.3 Historical Background

The history of used nuclear fuel disposal in the United States can safely be called a tumultuous one. Since the passage of the Nuclear Waste Policy Act (NWPA) by Congress in December 1982 and its subsequent approval by the President in January 1983, the United States has had a legal framework with which to deal with the inventory of used nuclear fuel [1]. The NWPA in 1982 established that a process for the selection of two permanent geological repositories for used nuclear fuel and other high-level radioactive wastes [2]. Additionally, the NWPA authorized the Department of Energy (DOE) to enter into contracts with utilities in order to being accepting their used nuclear fuel starting in 1998 [2]. The utility companies would get this service by paying a fee to the DOE of $0.001 (one-tenth of one cent) for every kilowatt hour of nuclear generated electricity sold [2]. These fees would go into a fund, called the Nuclear Waste Fund, that would be used to build the deep geological repositories and transport the used nuclear fuel there [2]. By 1986, the DOE had narrowed down the selection of a deep geological repository site to three potential locations: one in Washington state, one in Texas, and one at Yucca Mountain, Nevada [2]. However, in 1987 the NWPA was amended, resulting in many changes to the original act. Most importantly the 1987 amendment designated Yucca Mountain, Nevada as the only site that would be considered for a permanent deep geological repository and halted site characterizations of all other sites [2]. This amendment was very unpopular in Nevada and became known as the “Screw Nevada” bill [2]. Because Nevada was never really consulted on becoming the federally determined site for the entire nation’s used nuclear fuel inventory, strong public opposition began in Nevada.
Although the DOE was contractually obligated to begin accepting used nuclear fuel in 1998, it was not until 2002 when the DOE issued a formal report on the suitability of the Yucca Mountain site [2]. That same year, the Governor of Nevada exercised his state’s veto right to block the construction of Yucca Mountain; however, provisions in the NWPA allowed for both Congress and the Senate to override the veto and force Nevada to accept Yucca Mountain [2]. As Nevada had three representatives in Congress and two in the Senate compared to the remaining 49 states having 435 representatives in Congress and 98 in the Senate, it is little wonder how the Nevada veto was overridden. In 2008, the DOE submitted a complete license application for the Yucca Mountain facility to the Nuclear Regulatory Commission (NRC) for their review; however, in early 2009, spurred by the change in administration after the 2008 presidential and congressional elections, the DOE stated that Yucca Mountain was no longer a viable option. In 2010, the DOE and the new administration moved to withdraw the Yucca Mountain project license application that had originally been delivered to the NRC in 2008. Because of this action to remove the license application, numerous lawsuits by utility companies and states were filed against the DOE. Eventually in 2011, federal funding to the Yucca Mountain project was ended and the project essentially mothballed [2]. In 2012, the Blue Ribbon Commission on America’s Nuclear Future produced a report detailing the history of used nuclear fuel management and recommending a consent based approach, so that states would have an active role in the site selection process [2]. Unfortunately, since 2012 not much has been done to forward the Blue Ribbon Commission’s recommendation. In fact, in 2013 a federal appeals court ruled that the DOE must stop collecting the fees associated with the Nuclear Waste Fund since there is no work ongoing at the Yucca Mountain project. Additionally, that same year, another court ruled that the NRC had to resume the review of the original license application, since it was legally
required to do so. This review of the license application, entitled the Safety Evaluation Review, was released in January of 2015 and states that the Yucca Mountain site is suitable from a technical perspective; however, the Yucca Mountain project is still not being considered as a viable option by the current administration. Thus, the current state of used nuclear fuel management still remains certainly uncertain.

1.3 Motivation

The nuclear fuel cycle in the United States, specifically the back end portion, remains an unresolved issue. The back end portion of the nuclear fuel cycle is understood to be the methodology utilized for final disposal of used nuclear fuel and other radioactive wastes generated through nuclear power generation. The enduring issue of used nuclear fuel disposal continues to stain the reputation of the United States in terms of its energy policy leadership. In order to resolve this issue, numerous studies, reports, and commissions have been formed and yet, despite the tremendous effort, used nuclear fuel continues to be placed in dry casks outside of nuclear power plants with no clear time table on its final removal and final disposal [2]. 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 [3] [4] [5] [6].

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 [7]. 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 [2]. After performing their own analysis and investigation in 2012, the experts from The Blue Ribbon Commission on America’s
Nuclear Future recommended a transparent and consent based siting process for the construction of a deep geological repository as the best and most likely solution to the United States’ used nuclear fuel situation [2]. At present, not much has been done to forward and actualize this recommendation. Therefore, there is still motivation to find a solution the United States’ used nuclear fuel predicament that can somehow incorporate the preferences of members of the general public.

1.4 Objective

The objective of this work is to create a process that incorporates the preferences of members of the general public so that the selection of a nuclear fuel cycle can be based on both technical aspects and public acceptability, and most importantly present the results in a clear, transparent, and accountable manner. To present the results in a clear, transparent, and accountable manner it is necessary that members of the general public understand how their participation will affect the results, that the final results can be tied directly back to individual preferences, and that the final results be presented in a manner that members of the general public can easily understand them.

1.5 Approach

A method commonly used to incorporate multiple disparate aspects of complex decisions into the synthesis of a final decision is the main topic in the field of multiple objective decision analysis (MODA). In this work we will create a decision making model based on MODA principles to achieve our objective. Thus a model will be created to systematically evaluate multiple nuclear fuel cycles in terms of both their technical aspects and their public acceptability. There exist different methods in the field of MODA to aggregate and combine different disparate aspects of the decision
goal. It was therefore necessary and relevant to examine a few decision analysis methodologies and processes; these will be detailed in the subsequent chapter.
CHAPTER 2

SELECTION OF A MULTIPLE OBJECTIVE DECISION ANALYSIS PROCESS

2.1 General Components

There are three main components of any multiple objective decision analysis (MODA) methodology. The first is that each objective is given some relative importance in regard to the decision goal; this is usually represented as the weight of that objective, sometimes called the priority. The sum of these weights should add to one. An example of this would be that for the decision goal of selecting the best job, the objective of maximizing salary can be given a weight of 50% while the objective of minimizing commute time can be given 10% and maximizing the enjoyment of the work can be given the remaining 40%.

The second component is that each objective should have some function associated with it which brings its specific evaluation metric into the same evaluation space shared by all objectives. An example of this would be that for the same decision goal of selecting the best job, the different salary amounts, measured in dollars, be converted into personal utility, while the different commute times, measured in minutes, also be converted into personal utility, and likewise the different levels of enjoyment of the work, perhaps measured through a constructed scale of low, medium, or high, also be converted into personal utility. These personal utilities can then be directly compared against each other.

The third component is an aggregation method which combines all the objectives in some manner. The simplest of these would be a linear additive function where each
objective’s utility value is multiplied by its weight and the resulting decision goal is the sum of all the terms. The generic form of this can be seen below in Equation 2.1:

$$U_{A_1} = w_{O_1}U_{A_1,O_1} + w_{O_2}U_{A_1,O_2} + \ldots w_{O_n}U_{A_1,O_n}$$  \hspace{1cm} (2.1)$$

where $U_{A_1}$ is the final utility of the first alternative, $w_{O_n}$ is the weight of the $n^{th}$ objective, and $U_{A_1,O_n}$ is the utility of the first alternative with respect to the $n^{th}$ objective.

Many different methodologies and processes exist that incorporate these components with varying degrees of practicality, usefulness, and theoretical backing. With the decision goal of selecting the optimal nuclear fuel cycle that incorporates both technical and public acceptance aspects, two methodologies were selected that would allow this to be done. The methodologies selected were the Analytic Hierarchy Process (AHP) and Multi-Attribute Utility Theory (MAUT).

2.2 The Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP), as developed by Thomas Saaty in 1980, is a multi-criteria decision analysis (MCDA) methodology, which starts by first understanding a decision goal [8]. Once a goal is realized, such as selecting the optimal nuclear fuel cycle, all of the important criteria associated with that decision are listed [9]. The main criteria that affect the decision goal are then developed through expert knowledge, a literature search, and brainstorming amongst the stakeholders and the decision analyst [9]. Once these main criteria are developed, they are often realized to actually be composed of sub-criteria, and this process results in a structured hierarchy of criteria and sub-criteria [9]. The criteria on any one level of the hierarchy should be on the same order of magnitude in regards to their importance to the de-
cision goal; this is so meaningful comparisons can be made between the criteria [9]. A list of alternative solutions to the decision goal are also identified through expert knowledge, a literature search, and brainstorming amongst the stakeholders and the decision analyst [9].

After the decision goal and its relevant criteria and sub-criteria are organized into a hierarchy, the decision analyst elicits the relative importance of each criterion and sub-criterion. In AHP, this is done through pairwise comparisons. The comparisons are generally structured by a two step elicitation process. The first step is asking which criterion is more important, and the second step is then asking for the relative magnitude of importance. A brief example of this would be asking the question: “Which is more important for the selection of an optimal nuclear fuel cycle: Radiation Exposure or Proliferation Potential?” Additionally, the follow-up question is then asked “How much more important is that criterion compared to the other?” The respondent is also free to state that the criteria are equally important.

In answering the question “How much more important ...” the respondent is generally given a list of qualitative responses from which to choose. Use of a qualitative scale is done so that the respondent may answer in terms they are readily familiar with. In contrast, asking directly for the numerical magnitude of importance would be cumbersome if not entirely confusing for those not mathematically inclined. The qualitative terms are, in order of increasing magnitude of importance: equally, slightly, moderately, strongly, very strongly, and extremely [9]. The use of qualitative terms requires the interpretation of such results into quantitative values via some numerical interpretation scheme. The scheme proposed in the original AHP is of a simple linear one through nine scale such that equally important = 1, slightly = 2, moderately = 3, strongly = 5, very strongly = 7, and extremely = 9, times more important [9]. The reason for not using all nine degrees of preference, and instead using
six, is that participants have a more difficult time responding when presented with too many degrees of preference and give more consistent results when using around five [10]. The validity of this interpretation assumption, the inclusion of slightly, as well as alternative numerical interpretations are explored in §2.2.3.

The number of pairwise comparisons is a function of the number of criteria under evaluation in that level of the hierarchy. The number of pairwise comparisons is given by Equation 2.2:

$$N = \frac{n(n - 1)}{2}$$  \hspace{1cm} (2.2)

where $N$ is the number of pairwise comparisons and $n$ is the number of criteria under evaluation. Thus for a hierarchy level that contains seven criteria, 21 comparisons are needed to perform a comprehensive analysis. However, it is not strictly necessary to perform all of the pairwise comparisons if logical consistency is assumed. If logical consistency is assumed the number of pairwise comparisons that are required to be comprehensive reduces to $N = n - 1$. This is because the remaining evaluations can be derived from the first $n - 1$ evaluations, e.g., if A is three times greater than B and B is two times greater than C, then, to be logically consistent, A must be six times greater than C. However, logical consistency is in general not inherent in people’s decisions [9] [7]. Thus in AHP, all of the pairwise comparisons are done, and the degree to which they are logically consistent can be mathematically derived. This will be explained later in §2.2.1.

Once the complete number of pairwise comparisons are done according to Equation 2.2, these values are assembled into a matrix format. This is known as a decision or judgment matrix [9]. The decision matrix is always a square matrix of order equal to the number of criteria being compared [8]. The format of the matrix is to list the
criteria along the rows and columns of the matrix, where each matrix element represents the comparison of the row criterion to the column criterion [8]. For example, element (1,2) represents the comparison of criterion 1 to criterion 2, similarly element (2,1) should be the reciprocal of element (1,2) since it is the comparison of criterion 2 to criterion 1 [8]. Thus all values along the main diagonal are simply one since these elements represent a comparison of a criterion with itself [8]. The matrix follows the format shown in Equation 2.3:

\[
A = \begin{bmatrix}
1 & P_{1,2} & P_{1,3} & \cdots & P_{1,n} \\
\frac{1}{P_{1,2}} & 1 & P_{2,3} & \cdots & P_{2,n} \\
\frac{1}{P_{1,3}} & \frac{1}{P_{2,3}} & 1 & \cdots & P_{3,n} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
\frac{1}{P_{1,n}} & \frac{1}{P_{2,n}} & \frac{1}{P_{3,n}} & \cdots & 1
\end{bmatrix}
\]  \tag{2.3}

where \( A \) is the decision matrix populated with preference values \( P_{i,j} \), which is the preference of the \( i^{th} \) criterion to the \( j^{th} \) criterion.

The actual mathematics involved in deriving the priority of each criterion from the judgment matrix are not terribly complex. Once the decision matrix has been populated with its preference judgments the matrix is raised to a sufficiently high power [9]. Without raising the matrix to higher powers only direct dominance will be computed; however, if the matrix is raised to higher powers the more complete picture of the higher level dominances will be included, i.e., two-step, three-step, etc… [9]. This step can be seen in Equation 2.4:

\[
A' = A^k
\]  \tag{2.4}

where \( k \) is some sufficiently large number which will cause the later priorities to converge (sometimes this is as low as 2) and \( A' \) is the new decision matrix.
After the decision matrix is raised to a sufficiently high power, each column is summed as is illustrated in Equation 2.5 [9]:

\[ b' = \left\{ \sum_{i=1}^{n} A'_{i,1}, \sum_{i=1}^{n} A'_{i,2}, \sum_{i=1}^{n} A'_{i,3}, \cdots, \sum_{i=1}^{n} A'_{i,n} \right\} \quad (2.5) \]

where \( b' \) is the column summation vector.

The next step in AHP is to divide each column element in the new decision matrix by its column sum to normalize the columns. This is seen in the Equation 2.6:

\[
A'' = \begin{bmatrix}
\frac{A'_{1,1}}{b'_1} & \frac{A'_{1,2}}{b'_2} & \frac{A'_{1,3}}{b'_3} & \cdots & \frac{A'_{1,n}}{b'_n} \\
\frac{A'_{2,1}}{b'_1} & \frac{A'_{2,2}}{b'_2} & \frac{A'_{2,3}}{b'_3} & \cdots & \frac{A'_{2,n}}{b'_n} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
\frac{A'_{n,1}}{b'_1} & \frac{A'_{n,2}}{b'_2} & \frac{A'_{n,3}}{b'_3} & \cdots & \frac{A'_{n,n}}{b'_n}
\end{bmatrix} \quad (2.6)
\]

where \( A'' \) is the new decision matrix after having its columns normalized by their column sums.

The next operation in AHP is to sum the rows, and in this manner the principal eigenvector has been calculated [8]. This operation is seen in Equation 2.7:

\[
c'' = \left\{ \sum_{i=1}^{n} A''_{1,i}, \sum_{i=1}^{n} A''_{2,i}, \sum_{i=1}^{n} A''_{3,i}, \cdots, \sum_{i=1}^{n} A''_{n,i} \right\} \quad (2.7)
\]

where \( c'' \) represents the row summation vector.

The penultimate step is to simply compute the sum of every element in the row.
summation vector [9]. This step is seen in Equation 2.8:

\[ d'' = \sum_{i=1}^{n} c''_i \]  

(2.8)

where \( d'' \) is the elemental summation value of the row summation vector.

The final step is to simply normalize the row summation vector by dividing each element in the row summation vector by the sum of all of the elements in the row summation vector [9]. This final step is seen in Equation 2.9:

\[
\mathbf{c} = \begin{bmatrix}
\frac{c''_1}{d''} \\
\frac{c''_2}{d''} \\
\vdots \\
\frac{c''_n}{d''}
\end{bmatrix}
\]  

(2.9)

where \( \mathbf{c} \) is the vector of the final priorities (weights) of each criterion.

Just presented was the original Analytic Hierarchy Process’s method to take pairwise comparisons, assemble them into a matrix, and derive the priorities (weights) associated with each criterion. However, because of the nature of the preference judgments, as previously stated, logical consistency is not required. Yet, by performing the preceding operations one may arrive at perfectly reasonable priority values. For example, one may say A is three times greater than B, B is two times greater than C, and, logically inconsistently, that C is four times greater than A. Performing an AHP analysis on this would give the priorities of A being 30%, B being 29%, and C being 41%. It would be tempting for a decision analyst to state that criterion C is the most important based on its higher score, but this does not include the entirety of information present. It would be like a statistician choosing only on the basis of mean values, while disregarding the standard deviations. AHP includes a method
to calculate the inconsistency of a decision matrix, and a rule-of-thumb by which some responses with low-levels of inconsistency can be meaningfully accepted and the responses with high-levels duly expunged from the analysis. This methodology is presented in §2.2.1.

2.2.1 Inconsistency Analysis in AHP

Consistency is evaluated through the use of two quantities. The first quantity is known as the consistency index (CI) and is as follows:

\[ CI = \frac{\lambda_{\text{max}} - n}{n - 1} \]  

\(\lambda_{\text{max}}\) is the maximum eigenvalue of the judgment matrix, and \(n\) is the order of the matrix \([9]\). Thus when a decision matrix is perfectly consistent, the maximum eigenvalue is equal to the order of the matrix resulting in the consistency index being equal to 0.

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).

\[ CR = \frac{CI}{RI} \]  

\(\text{CR}\) is recommended by Saaty \([9]\).
Table 1. Random Index (RI) Values for 9 Degrees of Preference

<table>
<thead>
<tr>
<th>n</th>
<th>Integer</th>
<th>Balanced</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.525</td>
<td>0.267</td>
<td>0.387</td>
</tr>
<tr>
<td>4</td>
<td>0.883</td>
<td>0.437</td>
<td>0.646</td>
</tr>
<tr>
<td>5</td>
<td>1.108</td>
<td>0.547</td>
<td>0.813</td>
</tr>
<tr>
<td>6</td>
<td>1.251</td>
<td>0.620</td>
<td>0.922</td>
</tr>
<tr>
<td>7</td>
<td>1.341</td>
<td>0.671</td>
<td>0.997</td>
</tr>
<tr>
<td>8</td>
<td>1.404</td>
<td>0.710</td>
<td>1.051</td>
</tr>
<tr>
<td>9</td>
<td>1.450</td>
<td>0.739</td>
<td>1.091</td>
</tr>
<tr>
<td>10</td>
<td>1.486</td>
<td>0.761</td>
<td>1.122</td>
</tr>
</tbody>
</table>

2.2.2 Group Decisions in AHP

What has been discussed throughout §2.2 is deriving the priorities or weights for a single decision matrix. Still to be explored is the question of how to aggregate the judgments of multiple participants. There exist two methods in AHP for having consensus on the priorities of the criteria for a decision. The first method is to aggregate the individual judgments from each decision matrix into a group decision matrix, and then perform AHP on the group decision matrix treating it as a single entity to arrive at the group priorities [12]. The second method is to complete AHP on each individual decision matrix to arrive at each individual’s priority and then aggregate the resulting priorities to obtain the group priorities [12]. The first method of aggregating priorities is best used when all of the individuals are attempting to make a group decision that is best for the group, thus giving up their own identity for a group decision matrix [12]. While the second method of aggregating priorities is best used when the individuals are trying to express their own preferences and a group decision is trying to best take everyone into account, thus aggregating individual priorities [12]. Within the context of this manuscript, the second method of aggregating
individual priorities will be employed. Because AHP is based on ratios between criteria, the use of the geometric mean to aggregate values is the most meaningful [12]. Equation 2.12 describes the geometric aggregation of priorities:

\[ \hat{c}_i = \prod_{j=1}^{m} (c_{i,j})^{\omega_j} \]  

(2.12)

where \( \hat{c}_i \) represents the group priority for the \( i^{th} \) criterion by using the geometric mean, \( m \) represents the number of individuals whose preferences are combined, \( c_{i,j} \) represents the priority of the \( i^{th} \) criterion by the \( j^{th} \) individual, and the exponent \( \omega_j \) represents the importance weight of the \( j^{th} \) individual.

Alternatively, the arithmetic mean can still be used to get meaningful results, this is shown in Equation 2.13 [12]:

\[ \bar{c}_i = \sum_{j=1}^{m} \omega_j c_{i,j} \]  

(2.13)

where \( \bar{c}_i \) is the group priority for the \( i^{th} \) criterion by using the arithmetic mean. In both equations the importance weights \( \omega_j \) should sum to one.

The development of importance weights constitutes a recursive problem which is potentially without bound. For instance, if one wants to determine the weights of the judgment givers based on their qualifications for determining the correct weights of criteria, how does one then determine the weights of the individuals who are determining the weights of the judgment givers who are then determining the weights of the criteria. Similarly, this may go on ad infinitum. Eventually some scheme must be agreed on. In many cases, every individual is assigned the same equal weight, but there is no intrinsic reason why this should be the case, and a unique weighting scheme will need to be developed in any application of AHP or more generally for any MODA.
2.2.3 Numerical Interpretation Schemes in AHP

Qualitative terms are recommended for use by Saaty in the context of social, psychological, or political decisions [9]. Because the selection of a nuclear fuel cycle can easily fit in the categories of a social or political decision, qualitative terms were used to perform pairwise comparisons throughout this manuscript. However, qualitative terms must then be numerically interpreted after they are elicited. Saaty recommends a simple linear interpretation of qualitative terms [9]. However, the linear (integer) interpretation scheme has been challenged on the basis that the resulting derivable weights for the criteria are not uniformly distributed; meaning that if this scheme is used, only certain weights can be developed, and these potential weights tend to not evenly occupy the full space of all possible weights imaginable [10]. A further challenge to this scheme is based on psychophysical principles; for instance, perception of auditory stimuli follows a more logarithmic scale, while perception time duration tends to follow a more linear scale [13]. Because it is not at all certain what scale appropriately relates to an individual's magnitude of importance when performing pairwise comparisons of abstract criteria, the evaluation of multiple interpretation scales can be used to understand the bounds of the results.

Three numerical interpretation scales are the linear, balanced, and power scales. These scales can be seen numerically in Table 2 and graphically in Figure 2. Under the balanced scale, the derivable weights are exactly uniformly distributed for a decision with two criteria, but become progressively less uniform as the number of criteria under evaluation is increased [10]. The development of these values is from the following equation [10][11]:

\[ x_b = \frac{b}{(1 - b)} \]  \hspace{1cm} (2.14)

where \( x_b \) represents the balanced scale evaluation values, and \( b \) represents the balanced
scale input values. The values of $b$ are chosen so that the resulting scale generates evenly distributed weights. The values of $b$ are 0.5, 0.55, 0.6, ..., 0.9.

Under the power scale, the derivable weights are intended to be nearly uniform for any number of criteria under evaluation [10]. The values for the power scale are generated from the equation [10]:

$$x_p = (\gamma \sqrt{9})^a$$

(2.15)

where $x_p$ represents the power scale evaluation values, $\gamma$ is the number of increments of judgment used for comparing attributes, and $a$ is some integer from 0 to $\gamma - 1$; for our purposes $\gamma$ will be nine [10].

<table>
<thead>
<tr>
<th>Integer</th>
<th>Balanced</th>
<th>Power</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>Equal Importance</td>
</tr>
<tr>
<td>2</td>
<td>1.22</td>
<td>1.32</td>
<td>Slight Importance</td>
</tr>
<tr>
<td>3</td>
<td>1.50</td>
<td>1.73</td>
<td>Moderate Importance</td>
</tr>
<tr>
<td>4</td>
<td>1.86</td>
<td>2.28</td>
<td>Between Moderate and Strong Importance</td>
</tr>
<tr>
<td>5</td>
<td>2.33</td>
<td>3</td>
<td>Strong Importance</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>3.95</td>
<td>Between Strong and Very Strong Importance</td>
</tr>
<tr>
<td>7</td>
<td>4</td>
<td>5.20</td>
<td>Very Strong or Demonstrated Importance</td>
</tr>
<tr>
<td>8</td>
<td>5.67</td>
<td>6.84</td>
<td>Between Very Strong and Extreme Importance</td>
</tr>
<tr>
<td>9</td>
<td>9</td>
<td>9</td>
<td>Extreme Importance</td>
</tr>
</tbody>
</table>

No one scale is necessarily more valid than the others; however, the power and the balanced scale do have attractive attributes, i.e., the more uniform spacing of the
final derivable priorities, which merit their inclusion in an analysis performed with AHP.

2.2.4 AHP Value Functions

Although AHP has a thorough methodology in developing priorities (weights) for the different criteria of a decision model, comparatively little attention is given to the development of value or utility functions which are meant to bring disparate metrics into the same evaluation space. A way recommended by Saaty is to pairwise compare the metric values in terms of their preference, perform AHP, and use the resulting priorities of the metric values as the value function [9]. Additionally, there is no restriction on the value functions being framed in such a way that they are
2.2.5 AHP Final Aggregation

A typical method in AHP is to organize the different criteria into four main hierarchies, one of benefits, one of costs, one of opportunities, and one of risks, and then proceed with the analysis. This is known as a BOCR analysis.

Finally, once all the alternatives have been evaluated against the criteria, the weights of each hierarchy can be combined by using one of the following equations [14] [15]:

\[
P_a = w_b B + w_o O - w_c C - w_r R
\]

\[
P_m = \frac{w_b B + w_o O}{w_c C + w_r R}
\]

Where \( P_a \) is the final additive with subtraction priority of each alternative, \( P_m \) is the final multiplicative priority of each alternative, \( w_i \) is the weight of each hierarchy, \( B \) is the value of the benefits hierarchy, \( O \) is the value of the opportunities hierarchy, \( C \) is the value of the costs hierarchy, and \( R \) is the value of the risks hierarchy. Both Equations 2.16 and 2.17 are recommended for use because they always yield correct indications of profitability when all the criteria and alternatives have specific monetary values [14]. The final decision can then be determined from this analysis.

2.2.6 AHP Summary

The Analytic Hierarchy Process represents an intuitive way to make judgments about multiple criteria, often grouped under the hierarchies of benefits, costs, opportunities, and risks. AHP is used to help determine which criteria are the most important to a decision goal. The judgments that are required for AHP are elicited by qualitative pairwise comparisons; after which, they are numerically interpreted.
and assembled into a decision matrix. The weights of each criterion can be found by computing the principle eigenvector of the decision matrix. These weights can be used to rank criteria in terms of their importance, as well as give a magnitude to that level of importance. AHP also contains a method by which one may evaluate the consistency of individuals’ judgments; which can be used to remove highly inconsistent respondents from the data. The development of value functions for the different criteria can be generated by similarly performing pairwise comparisons on the importance of changes in the range of each criterion. With value functions and the weights of each criterion, the different alternatives can be ranked against each other so that an optimal solution may be found.

Like learning a new language and subsequently developing a deeper understanding of the limitations and benefits of one’s arterial language, it is necessary to investigate an additional MODA methodology to understand more deeply the limitations and benefits of AHP. This additional methodology is know as Multi-Attribute Utility Theory (MAUT).

2.3 Multi-Attribute Utility Theory

Note: the majority of this section, and the majority of the author’s understanding of MAUT is based off of a class that the author completed in Fall 2014 entitled Multi-objective Decision Analysis with Dr. Jason R. W. Merrick. As such, this section should not be taken to be the original work of the author and is included so that the reader may have the same understanding of MAUT that the author has.

The general process of decision analysis by using Multi-Attribute Utility Theory (MAUT) is centered around developing a set of coherent objectives that each alternative decision will be evaluated against. These objectives are analyzed and evaluated so that they fundamentally describe the decision at hand. It is important
when generating these objectives to continue to ask the question “Why is this important?” [16]. In doing so three types of objectives are identified; means objectives, fundamental objectives, and strategic objectives [16]. Means objectives are objectives which are desirable to maximize or minimize but not because of an inherent value, rather they are a means to achieving something else that is inherently valuable [16]. A fundamental objective is an objective which has inherent value, but is also completely determined by the decision at hand, i.e., no decisions except for the primary decision should affect the value of this objective [16]. Finally, a strategic objective is an objective that is inherently valuable, but is influenced by many different decisions other than the decision at hand [16]. To get from means to fundamental to strategic one generally asks the question “Why is this important?” repeatedly until the answer is “Because it is.” This can best be seen in an example: for the decision goal of choosing the safest method of nuclear fuel disposal an objective might be generated such as minimize radiation exposure to the general public from the disposal method. Although this looks like a meaningful objective, when asked “Why is this important?” the answer will be to minimize the rates of radiation induced cancer in the general public from the disposal method. If the same question is applied again the answer will be to maximize the lifespan of members of the general public. Now, if “Why is this important?” is asked again we should rationally arrive at “Because it is.”

To recollect the process and evaluate what just happened we will find that our initial objective, minimize radiation exposure to the general public from the disposal method, is in fact a means objective. This is because there is no reason we should intrinsically try to limit our radiation exposure, rather we want to limit our radiation exposure because we perceive that doing so will help us stay healthy. By asking “Why is this important?” we have driven the previous means objective to another objective, minimize the rates of radiation induced cancer in the general public from the disposal method.
method. Now this objective seems to be fundamental, in that it is describing what is intrinsically valuable, while being fully encompassed by the decision goal. As a way of checking if we have correctly identified the fundamental objective, we again ask “Why is this important?” to arrive at the objective maximize the lifespan of members of the general public. Now although this may be an even deeper fundamental reason, we want to avoid cancer, the objective has many other influences outside the context of the decision of nuclear waste disposal; for example, public health decisions about diet, exercise, vaccinations, etc., will all factor into the objective maximize the lifespan of members of the general public, and thus the objective is strategic. This process can be seen in Figure 3. Once all of the relevant fundamental objectives have been determined they can be grouped by likeness, typically into a hierarchy [16].

It is an important part of MAUT that the decision be made entirely of fundamental objectives [16]. Once the fundamental objectives are identified, they are also framed in such a way that they will be monotonic along the range they are evaluated [8]. Monotonic means that for every value of the objective either more will always be preferred to less or the reverse, i.e., less will always be preferred to more [17]. If an
objective is not monotonic, i.e., some optimal value is located between the highest plausible value and the lowest plausible value, the fundamental objective is not truly being evaluated. This is because any non-monotonic function can be composed of at least two monotonic functions which will in fact be the fundamental ones.

An additional requirement of fundamental objectives in MAUT is to have a defined range about which the evaluations will take place. Not having a defined range would lead to meaningless assessments of value according to Keeney [18]. For example if one was trying to select a new job the question might arise “What is more important, minimizing commute time or maximizing salary?” The correct answer should be “It depends.” If the range of commute times for the jobs under evaluation was between 20 minutes and 25 minutes, while the range of salaries for the jobs was between $50K and $150K, then maximizing salary would be more important since an additional five minutes of commute time is generally minuscule compared to a $100K increase in salary. While just the opposite would occur if the range of commute times was between 10 minutes and 120 minutes and the salary range was between $80K and $82K. Thus it is very important that the range be defined when evaluating the weights of the objectives in MAUT [18]. To develop the weights of the objectives, a method known as swing weights can be employed.

2.3.1 Swing Weights

With the fundamental objectives determined and a range of alternatives chosen, the weight of each objective needs to be determined. It is necessary to apply a weight to each objective commensurate with its value for the decision. The method of swing weights is used in MAUT for its ability to account for the range in value of each objective and also to assure that rank reversals are impossible. To elicit the weights, a stakeholder or a group of stakeholders is typically utilized.
The method of swing weights is as follows: one first imagines a hypothetical alternative in which all of the objectives on a single branch of the decision hierarchy are at their worst value. The individual then selects an objective; which, if raised to its best value would have the greatest impact on the decision amongst those in that branch. This objective is then assigned a value of 100. Removing that objective, the remaining objectives are then reevaluated to determine which objective that when raised to its best value would have the next greatest impact on the decision. This objective is then compared against the objective already assigned a value of 100 and its relative value is determined to be equal to or less than 100, i.e., assigning this objective a value of 50 would mean that it is half as important to the decision as the first selected objective. Similarly, this process is repeated until all the objectives have values. The values are then normalized to acquire the weights of those objectives within that branch. Once each objective on every branch has been weighted, the branches are evaluated against the other branches. This is done by imagining that every objective on a branch is at its worst value. Then, by imagining taking all objectives on a branch from their worst values to their best values, the branch that has the greatest impact on the decision is selected and given a value of 100. As in the case with the individual objectives the other branches are assigned values relative to the first selected branch. The values are then normalized to acquire the branch weights. This process can be repeated moving up the hierarchy for as many branches that exist within the decision. To determine the global weight of an objective simply multiply the weight of that objective within that branch by the weight of each branch it falls under.

Knowing the weight of each objective is only one piece if the puzzle, and some sort of value function is required to bring each variable from its objective’s evaluation space, such as dollars or the number of cancers induced, to the decision value space.
shared by the objectives. This is done by the use of monotonic functions known as single-dimensional value functions (SDVF) or single-dimensional utility functions (SDUF).

### 2.3.2 Single-dimensional Value Functions

Single-dimensional value functions (SDVF) are the functions that translate the objective from its evaluation space into the shared value space. If the objectives are fundamental, then every single-dimensional value function will be monotonic. To obtain the single-dimensional value functions the following elicitation method is used. Each fundamental objective has its best value on its range assigned a 100 and its worst value on its range assigned a 0. This means for an objective at its best measured value, the value which can be derived from that objective is 100, while at its worst values the value which can be derived from that objective is 0. Once these ranges and the maximum and minimum values of the objectives are established, each range can be further partitioned to better understand the shape of the value function. When the objective has a natural scale, the midpoint of the range can be evaluated by the method demonstrated in the following example.

For an objective such as the one previously discuss of maximizing salary at a new job given the first range, $50K to $150K, the objective value and decision value pairs would be as follows ($50K, 0) and ($150K, 100). The midpoint on this range representing a salary of $100K is evaluated for its value ($100K, \( V_{100K} \)). This value is elicited by imagining the change to and from that point by asking the question: “Is it more important to go from a salary of $50K to $100K? Or is it more important to go from a salary from $100K to $150K? Or is it about the same?” Once this is determined, it immediately brackets the possible values which \( V_{100K} \) can take. If it is more important to go from a salary of $50K to $100K, then the possible range of
values which \( V_{100K} \) can take is between 50 and 100. Similarly, if it more important to
go from a salary of $100K to $150K then the possible range of values which \( V_{100K} \) can
take is instead between 0 and 50. If the importance of each range is about the same,
then the value \( V_{100K} \) is exactly 50, and the analysis continues onto a new partition value.

Once it is determined which partial swing range is more important, the question
is asked: “How much more important?”. If the evaluator can give one, a numerical
value of the magnitude of importance is preferred to a subjective term, such as *slightly*
more important. This is because the subjective term would subsequently have to be
interpreted in some fashion into a numerical value anyway. If, for example, the swing
along one half-range is \( Z \) times as important than the swing along the other half-
range, then \( V_{100K} \) can be determined through one of the following equations.

\[
V_{(\text{half}|UR)} = V_{\text{min}} + \frac{V_{\text{max}} - V_{\text{min}}}{Z + 1} \tag{2.18}
\]
\[
V_{(\text{half}|LR)} = V_{\text{max}} - \frac{V_{\text{max}} - V_{\text{min}}}{Z + 1} \tag{2.19}
\]

where \( V_{(\text{half}|UR)} \) denotes the value at the half-range given that the upper-range is
selected as the more important range, \( V_{(\text{half}|LR)} \) denotes the value at the half-range
given that the lower-range is selected as the more important range, \( V_{\text{max}} \) denotes the
maximum value of the range in question, \( V_{\text{min}} \) denotes the minimum value of the
range in question, and once again \( Z \) denotes the magnitude of importance that the
selected half-range is over the other half-range.

The process can be repeated, bisecting the new ranges and eliciting a midpoint
value, as many times as is needed to resolve the function into a operable form. However,
it is important to bear in mind that after a certain number of elicitations the
function will be sufficiently resolved that the extra time taken to further resolve the

\[
\text{...}
\]
function will not be justified as the results will not differ significantly. Additionally, those individuals undergoing the elicitation will appreciate not having to be asked an excessive amount of questions. SDVF’s work well for deterministic objectives where the value of the objective can be known with a high degree of certainty. However, for objectives that have high degrees of uncertainty in their measured values an alternative approach is needed.

2.3.3 Probabilistic Inputs

When assigning values to the different objectives for each alternative, it often occurs that the input is not a single value but a distribution of values. It is insufficient to simply assign the value of the mean as the value for the objective since this does not account for the uncertainty around the value. Alternatively, what can be done is to apply a distribution to each value for continuous variables, and a probability of occurrences for ordinal variables. With these probabilities and distributions it is perhaps simplest to solve the final utilities by using a Monte Carlo sampling simulation. This involves taking random samples based on those probabilities and distributions to populate the objective values and then recording the results and repeating this process thousands of times so that a distribution of utilities can be obtained. The mean of this distribution of utilities will give the final utility of the alternative.

2.3.3.1 Continuous Functions

For continuous functions it can be assumed that distributions of objective values would follow a triangular distribution, whose shape is determined by a minimum possible value, a most likely value, and a maximum possible value. These values can be elicited by having the evaluator give the most likely value which the alternative would have for that objective, and then by giving the lowest possible value for the
objective which that alternative could take on and then the highest possible value it could ever have. Understanding that most people are overconfident in their assessment of values, the bounds can be widened if deemed necessary.

2.3.4 Single-dimensional Utility Functions

With the uncertainty introduced by the probabilities it may be no longer sufficient to use value functions to evaluate the model. Utility functions have a different elicitation mechanism and account for this uncertainty by eliciting values based on gambles. Because the utility functions are based on probabilities they are scaled from 0 to 1 instead of 0 to 100 as with value functions. The worst value has a utility of 0 and the best value has a utility of 1. The elicitation follows an iterative approach toward convergence on indifference probabilities. These indifference probabilities are then used for the utility function to represent the objective’s utility at that level. An example of this elicitation technique will be demonstrated in the following section, §2.3.4.1.

2.3.4.1 The Two Ticket Utility Gamble

In this approach, the evaluator is given the choice between purchasing one of two tickets. The first, Ticket A, has two probabilities associated with it. The first probability is that the objective under evaluation is found to be at the best possible value of the entire range, and the second probability is that the objective is found to be at the worst possible value of the entire range. The second ticket, Ticket B, is a ticket that leads to an assured outcome of the objective having some intermediate value. The utility of that intermediate value is the probability of the best value in Ticket A when the evaluator is indifferent between buying Ticket A or Ticket B. This approach can be demonstrated with an example using the same continuous objective
from §2.3.2, i.e., salary of a specific job. The first gamble is presented in Figure 4, and can be explained as follows.

![Fig. 4. Gamble for Utility on Objective Value of $100K, First Iteration](image)

Ticket A represents a gamble given some probability $p$, in this case 0.5, that the objective will be at its best value, a salary of $150K, and another probability $1-p$, in this case also 0.5, that the objective will be at its worst value, a salary of $50K. Ticket B represents an assurance that the objective will be at some intermediate value, in this case a salary of $100K. The evaluator then selects which gamble they would prefer. For the sake of the example, let us assume in this case the evaluator selected Ticket B. Because Ticket B is chosen it means that the probability of occurrence for the best value in Ticket A is not high enough, and should be raised. The probability of occurrence of the best value can now be raised to some value, such as 0.75. The second iteration on this gamble is presented in Figure 5.

Again, the evaluator may choose Ticket B, thus the probability of the best value of Ticket A must once again be increased. This time the probability is increased to 0.85. The third iteration on this elicitation is presented in Figure 6.

At this point the evaluator may be indifferent between purchasing Ticket A or Ticket B. Thus the utility for the a salary to pay $100K is 0.85. The same methodology
Utility functions will tend to exhibit either risk-averse or risk-seeking logarithmic shapes.

### 2.3.5 Global Utility Function

To evaluate the utility of an alternative from the probabilistic input, the utility function, and the weight that is applied to the objectives, some global aggregating function is needed. There are several methods of combining these, but a straightforward and valid approach is to utilize a linear additive form. The simplest linear
additive form can be seen in Equation 2.20, where the utility of alternative 1 is simply the weighted sum of all the objective utilities:

\[ U_1(x_1, \ldots, x_n) = \sum_{i=1}^{n} w_x U_1(x_i) \]  

(2.20)

here \( U_1 \) represents the utility of alternative 1, with respect to objective \( x \), \( n \) represents the number of objectives, and \( w \) represents the global weight of that objective.

This form is valid under single-dimensional value functions, if the objectives are mutually-exclusive and preferentially independent. However, when dealing with utilities, even if objectives are mutually-exclusive and preferentially independent, interaction terms still arise because of the uncertainties. These interaction terms have weights associated with them, and thus the swing weights are not strictly valid. However, the interaction terms are often negligible and for the most part can be dropped out without an appreciable loss in the validity of the final utility value. All of these interaction weights can be theoretically dropped out if two objectives are utility independent, see §2.3.5.1 [19]. This is good since the total number of weights including interactions increases by the following equation:

\[ N_w = 2^n - 1 \]  

(2.21)

where \( N_w \) is the total number of weights including all interactions and \( n \) is the total number of objectives being evaluated. Yet, despite dropping the majority of the interaction terms, a few bivariate terms can still be evaluated as to not lose too much validity. Thus the full form of the utility function that also includes bivariate interactions is given by Equation 2.22:

\[ U_1(x_1, \ldots, x_n) = \sum_{i=1}^{n} w_i U_1(x_i) + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} w_{ij} U_1(x_i) U_1(x_j) \]  

(2.22)
where $w_{ij}$ represents the interaction weight between the $i^{th}$ and the $j^{th}$ objectives.

Even reduction to the bivariate case still leaves a large number of weights to evaluate; however, the vast majority of even these bivariate interaction weights tend to be negligible and can reasonably be ignored.

### 2.3.5.1 Utility Independence

Two objectives are mutually utility independent if one is indifferent between the following gambles in Figure 7 [19], where a star (*) denotes an objective at its best value, and a naught (◦) denotes an objective at its worst value. Although theoretically sound, this is of little practical use as it depends on a judgment of four separate outcomes and even experienced evaluators find answering this question cumbersome and confusing.

![Mutual Utility Independence Condition](image)

Fig. 7. Mutual Utility Independence Condition

### 2.3.6 MAUT Summary

MAUT has a strong theoretical grounding, is based on a consistent set of axioms, and is fairly comprehensive in its scope. MAUT bases its analysis on fundamental objectives that have been thought about to a large degree, and continues to analyze each term systematically with a consistent method for developing objective weights,
the aggregating functions, and the global functions. It also includes uncertainty and
distributions into its analysis of alternatives. The major downside of MAUT is its
relative difficulty in being grasped by participants and the resulting fact that it may
be hard to operationalize.

2.4 Decision Making Methodology Used

The author was only aware of AHP at the start of undertaking this research,
and only later became aware of the existence of MAUT. For this reason, a hybrid
approach of AHP and MAUT is utilized, with AHP covering much of the initial
work and research, and MAUT covering the later work to fill in the gaps left by
AHP. MAUT is preferred for its in-depth thinking regarding the objectives being
evaluated compared to AHP’s brainstorm approach, for the inclusion of probabilities
and the distributions of values, and for having a formal method with which to evaluate
value functions. AHP does have the attractive quality of being a simpler approach,
with questions that may be more easily understood by the general public. By using
this hybrid approach, a sort of self-check can also be done since evaluating by two
methodologies should be superior than evaluating with simply one.
3.1 Alternative Nuclear Fuel Cycles

In the process of selecting an optimal nuclear fuel cycle for the United States, it was relevant to determine which nuclear fuel cycles would be initially evaluated. Those presented here are by no means the only fuel cycles that may be considered during such an analysis. By selecting nuclear fuel cycles that are currently being considered by the U.S. Department of Energy (DOE), a set of “most-likely” nuclear fuel cycles was created. Additionally, a few alternative nuclear fuel cycles that remain popular were included for comprehensiveness. In total there were ten nuclear fuel cycles chosen. The first seven alternatives focus on a strategy known as the ‘once-through’ fuel cycle. The ‘once-through’ fuel cycle assumes that once the used nuclear fuel leaves the reactor it will not be utilized for further energy production on any timescale. The next two fuel cycles assume some sort of recycling and reprocessing is utilized on a large scale and most commercial reactors start to generate electricity partially from the energy of these recycled components. The final alternative assumes that a new Generation IV reactor type is implemented on a large scale and reprocessing and recycling of used nuclear fuel takes place within this new technology. The alternative fuel cycles are listed below.

- On-Site Dry Cask Storage (A1)
  - The general method of on-site dry cask storage is to allow spent fuel to cool for a period of about five years in storage pools and then transfer the
spent fuel to a canister that is both cooled by natural circulation of air and properly shielded [2] [1]. The containers are then stored at the reactor sites for an undetermined period of time. Full implementation of this scheme is essentially ongoing and requires no additional action [2].

- **Permanent Consolidated Dry Cask Storage (A2)**

  - This case follows On-Site Dry Cask Storage with the use of dry casks; however, these dry casks are then transported away from the reactor sites to a national facility where they are stored permanently above ground. Full implementation of this scheme involves having legislation in place that allows this method to be done legally, constructing a facility where the used nuclear fuel can be brought, and constructing a transportation network with which to collect the used nuclear fuel.

- **Interim Consolidated Storage then Permanent Geological Repository: Closed (A3)**

  - In this case, newly discharged spent fuel is cooled in storage pools for a period of time, about five years, and then transported to a national interim facility where it is consolidated above ground. Additionally, existing dry casks are also transported the national interim facility and consolidated. After being consolidated, the fuel is then sent to a national permanent geological repository. After the national permanent geological repository has reached its limit on the amount of spent fuel it can accept, the facility is closed and backfilled to permanently seal the spent fuel away from the biosphere. Full implementation of this scheme involves having legislation in place that allows this method to be done legally, constructing both
the intermediate facility and permanent repository, and constructing a transportation network with which to collect the used nuclear fuel.

- Interim Consolidated Storage then Permanent Geological Repository: Retrievable (A4)
  
  This case is a variation of Interim Consolidated Storage then Permanent Geological Repository: Closed. The variation being that instead of closing and backfilling the facility when it has reached its limit on the spent fuel it can accept, the facility is maintained and guarded continuously. This allows for the option of retrieving the spent fuel if new technology, economics, or politics permits the utilization of such. Full implementation of this scheme involves having legislation in place that allows this method to be done legally, constructing both the intermediate facility and permanent repository, and constructing a transportation network with which to collect the used nuclear fuel.

- Direct Permanent Geological Repository: Closed (A5)
  
  In this case, newly discharged spent fuel is cooled in storage pools for a period of time, after which it is transported directly to a national permanent geological repository. Additionally, existing dry casks are also transported directly to the national permanent geological repository. After the national permanent geological repository has reached its limit on the amount of spent fuel it can accept, the facility is closed and backfilled to permanently seal the spent fuel away from the biosphere. Full implementation of this nuclear fuel cycle involves constructing a permanent repository and constructing a transportation network with which to collect the used nu-
clear fuel.

- **Direct Permanent Geological Repository: Retrievable (A6)**
  - This case is a variation of Direct Permanent Geological Repository: Closed. The variation being that instead of closing and backfilling the facility when it has reached its limit on the spent fuel it can accept, the facility is maintained and guarded continuously. This allows the option of retrieving the spent fuel if new technology, economics, or politics permits the utilization of such. Full implementation of this nuclear fuel cycle involves constructing a permanent repository, and constructing a transportation network with which to collect the used nuclear fuel.

- **Deep Borehole Disposal (A7)**
  - In this case, boreholes approximately 45 centimeters in diameter and 4 to 5 kilometers deep are drilled into the earth and cased [20]. The bottom 1 to 3 kilometers are filled with spent fuel and the rest is backfilled to permanently seal the spent fuel away from the biosphere [20]. Full implementation of this scheme involves developing deep borehole drilling technology, having legislation in place that allows this method to be done legally, and constructing a transportation network with which to collect the used nuclear fuel.

- **Spent Fuel Reprocessed and Recycled in Existing LWRs: Foreign (A8)**
  - In this case, spent fuel is removed from reactors and sent to an existing foreign reprocessing facility, e.g., in France. The extracted plutonium is blended with depleted uranium and is reprocessed into mixed-oxide fuel
Additionally, the reprocessed uranium is re-enriched for use as standard uranium oxide fuel. The fuel is then returned to the United States where it is re-utilized in existing light water reactors (LWRs). The high-level waste is also returned to the United States and is disposed of using one of the once-through methods. Full implementation of this method involves developing an agreement with a country for the reprocessing of U.S. owned used nuclear fuel, having legislation in place that allows this method to be done legally, constructing a transportation network with which to collect and transport the used nuclear fuel, and constructing a permanent repository for the disposal of high-level waste.

- **Spent Fuel Reprocessed and Recycled in Existing LWRs: Domestic (A9)**
  - This case is a variant of Spent Fuel Reprocessed and Recycled in Existing LWRs: Foreign. However, in this case instead of sending the spent fuel to an existing foreign reprocessing facility, a reprocessing facility is constructed in the United States and the spent fuel is transported directly to that location. Full implementation of this scheme involves constructing a used nuclear fuel reprocessing facility, having legislation in place that allows this method to be done legally, constructing a transportation network with which to collect and transport the used nuclear fuel, and constructing a permanent repository for the disposal of high-level waste.

- **Sodium-cooled Fast Breeder Reactor Implementation (A10)**
  - In this case, there is a large research investment and push into constructing sodium-cooled fast breeder reactors. New nuclear fuel is made within these new reactors and this fuel, in addition to the used nuclear fuel,
is reprocessed and utilized to make electricity. Full implementation of this nuclear fuel cycle involves having legislation in place that allows this method to be done legally, developing the technology to operate commercial sodium-cooled fast breeder reactors, constructing multiple sodium-cooled fast breeder reactors, constructing a transportation network with which to collect and transport the used nuclear fuel, and constructing a permanent repository for the disposal of high-level waste.

3.2 Justification and Discussion

These alternatives were mainly derived from the Blue Ribbon Commission Report as well as several other sources [2][1][4]. The list was vetted by the National Technical Director of the U.S. DOE Used Fuel Disposition Campaign during a conference call in March 2014 and the list was determined to be adequate and well aligned with the current U.S. government strategy.

Although certainly more than ten nuclear fuel cycles have been imagined, truly thousands of permutations exist, it is prudent to examine those considered most aligned with current U.S. government strategy. Additionally, through analyzing these ten, a greater understanding of the important aspects of a nuclear fuel cycle will be developed so that evaluation time may be saved in the future by only evaluating those fuel cycles likely to align with the important aspects of a nuclear fuel cycle.

In this manuscript a model has been constructed to systematically evaluate each alternative nuclear fuel cycle. This evaluation is done based on evaluating each alternative nuclear fuel cycle against different objectives to arrive at a ranking of alternative choices. An initial model for doing this is detailed in the next chapter.
NUCLEAR FUEL CYCLE OBJECTIVES: INITIAL AND REVISED

This majority of this chapter, Ch. 4, has been taken from the author’s previous work [21]. The initial analysis and revision were undertaken from an AHP perspective and did not include the development of fundamental objectives, as the technique to develop fundamental objectives was not yet in the author’s repertoire.

4.1 Introduction to Determining Objectives

Certainly one of the most difficult problems in any MODA project is the development of the relevant fundamental objectives. There are many common mistakes that occur when developing objectives, but of paramount importance is checking that each objective has five recommended requirements, specifically that the objectives are unambiguous, comprehensive, direct, operational and understandable [18] [22]. These requirements will be discussed further in the following section, §4.2.

4.2 Important Requirements of Objectives

Selecting objectives 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 objectives are both unambiguous and understandable. That an objective should be unambiguous is to say that the consequences from that objective should scale accordingly with the levels associated with that objective [22]. Additionally, the greatest effort must be given to
avoid vagueness and imprecision [22]. 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 objectives that are unambiguous is especially important so that proper comparisons can be made between the different objectives to assess their relative importance.

That the objectives 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 an objective, 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 [5]. 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 cancers [23], 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 objectives, 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 objectives that are understandable to the general public cannot be stressed enough.

Additionally, the objectives need to be comprehensive, that is covering the full range of consequences of an objective, direct, that is describing in a definite manner the consequences of interest, and operational, that is the information required for the evaluation of the objective can actually be obtained [22]. Finally, if the model were to attempt to utilize linear functions to develop the final weights for the objectives, an additional requirement will be needed to maintain the validity of this assumption. This requirement is that each objective must be mutually exclusive of the rest of the objectives. Developing objectives is an iterative process and the development of the objectives in this analysis has undergone many changes. A short review of the initial development of the decision objectives is presented in the following section.
4.3 Development of Decision Objectives

The development of decision objectives within the current analysis has undergone many iterations. To confirm that these objectives were not chosen without due care and extensive thought, the development process will be examined.

4.3.1 Initial Objectives Generation

To begin to evaluate multiple nuclear fuel cycles against common objectives 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 United States. A final step in generating the initial objectives was brainstorming between members of the research group. An initial list was constructed and can be seen below in Table 3. The hierarchies were separated into four sections pertaining to the benefits, opportunities, costs, and risks (BOCR) involved in choosing a specific fuel cycle.

<table>
<thead>
<tr>
<th>Benefits</th>
<th>Costs</th>
<th>Opportunities</th>
<th>Risks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disposition Flexibility</td>
<td>Facility Construction &amp; Maintenance</td>
<td>American Nuclear Development</td>
<td>Feasibility</td>
</tr>
<tr>
<td>Fuel Requirement Reduction</td>
<td>Infrastructure Development</td>
<td>Decommissioning Allowance</td>
<td>Potential Future Burden</td>
</tr>
<tr>
<td>Infrastructure Development</td>
<td>Legal Fees</td>
<td>Energy Policy Leadership</td>
<td>Proliferation Potential</td>
</tr>
<tr>
<td>Legal Resolution</td>
<td>Licensing &amp; Fines</td>
<td>Long-term Energy Security</td>
<td>Public Perception</td>
</tr>
<tr>
<td>Local Improvements</td>
<td>Proliferation Prevention</td>
<td>Promote Nuclear Industry</td>
<td>Radiotoxicity</td>
</tr>
<tr>
<td>Nuclear Political Stability</td>
<td>Transportation</td>
<td>Technology Development</td>
<td>Supply Availability</td>
</tr>
</tbody>
</table>
4.3.1.1 Benefits

The following were the definitions for the benefits objectives:

- **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.
4.3.1.2 Costs

The following were the definitions for the costs objectives:

- **Facility Construction & Maintenance**
  - Costs 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).

- **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.

- **Transportation**
  - Costs associated with the transportation of the used fuel, (interstate railways, trucks, barges, etc.) including their maintenance.

- **Waste Amount**
  - The cost associated with disposing of the sheer amount of the waste developed.
4.3.1.3 Opportunities

The following were the definitions for the opportunities objectives:

- **American Nuclear Development**
  - The opportunity of utilizing American resources, technology, labor 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 be developed.

- **U.S. Government Competence**
  - The opportunity that the selected fuel cycle improves U.S. citizens’ attitude toward the U.S. government’s competence.
4.3.1.4 Risks

The following were the definitions for the risks objectives:

- 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.
4.3.2 Initial Objectives Evaluation

Four separate paper surveys of these initial objectives, one for each hierarchy, were taken to a large nuclear engineering and science conference, and conference attendees were asked to pairwise compare the relative importance of objectives against each other, as per AHP methodology. A sample of the pairwise-comparison questions that were on the surveys that were handed out is shown below in Table 4, and the original surveys are included in Appendix L. The possible responses for the magnitude of importance were limited to the qualitative terms, *slightly*, *moderately*, *strongly*, *very strongly*, and *extremely*. Additionally, the respondents were free to write *equally important*. These responses were interpreted using the 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. After collecting the responses, the weights were computed through AHP. The results with no consistency index threshold and with a 10% consistency index threshold can be seen in Appendix E. Evaluating the consistency of the responses, it was shown that a large percentage of the respondents’ judgments failed to meet the consistency threshold of 10%. This trend can be seen in Table 5.

Table 4. Pairwise Comparison Example

<table>
<thead>
<tr>
<th>Criteria A</th>
<th>Criteria B</th>
<th>Which one is more important?</th>
<th>How much more important?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disposition Flexibility</td>
<td>Fuel Requirement Reduction</td>
<td><em>A</em></td>
<td><em>Moderately</em></td>
</tr>
<tr>
<td>Disposition Flexibility</td>
<td>Infrastructure Development</td>
<td><em>Equal</em></td>
<td><em>Equal</em></td>
</tr>
</tbody>
</table>

It was conjectured that a primary contributing factor to the high percentage of inconsistent responses was likely derived from the objectives not being well-defined, and not containing the previously mentioned five desirable factors. Some problems were determined to be vagueness in the previous definitions, having non-mutually
Table 5. Sample Sizes of Surveys Collected at Large Nuclear Engineering and Science Conference

<table>
<thead>
<tr>
<th>Group</th>
<th>No Threshold</th>
<th>20% Inconsistency</th>
<th>15% Inconsistency</th>
<th>10% Inconsistency</th>
<th>Percent Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benefits</td>
<td>15</td>
<td>12</td>
<td>12</td>
<td>7</td>
<td>53%</td>
</tr>
<tr>
<td>Costs</td>
<td>11</td>
<td>9</td>
<td>8</td>
<td>7</td>
<td>36%</td>
</tr>
<tr>
<td>Opportunities</td>
<td>11</td>
<td>8</td>
<td>6</td>
<td>3</td>
<td>73%</td>
</tr>
<tr>
<td>Risks</td>
<td>11</td>
<td>6</td>
<td>4</td>
<td>3</td>
<td>73%</td>
</tr>
<tr>
<td>Total</td>
<td>48</td>
<td>35</td>
<td>30</td>
<td>20</td>
<td>58%</td>
</tr>
</tbody>
</table>

exclusive objectives, and having objectives that are not relevant within the decision context. These problems were especially important to resolve considering the high inconsistency of the initial sample was mostly from individuals knowledgeable in the subject matter, who should be expected to make clear and consistent judgments. Since one of our primary audiences is the general public, it was expected that the same survey would lead to much larger inconsistency rates among that population.

In order to understand which specific objectives were most likely ill-defined, an analysis of the geometric variance was done for each objective at each consistency threshold. Since only the geometric variance of a comparison of two objectives can be determined, it was assumed that each of the objective’s relevant comparison variances would be summed equally. For example, when comparing Disposition Flexibility to Legal Resolution a geometric variance of 5.67 was found. This value would populate the first value for each objective, and since seven objectives 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 objective. For example, the average variance associated with the first objective, would be given in Equation 4.1:
where \( \sigma^2_{g(1)} \) is the average geometric variance associated with the first objective, \( \sigma^2_{g(1,j)} \) is the geometric variance of the comparison of objective 1 with objective \( j \), and \( n \) is the number of objectives, which in our case is seven.

This was done for each objective and the results can be seen in Table 6. It should be noted that a geometric variance of exactly one represents perfect alignment. There are two possible ways to interpret the reason for a objective having a high geometric variance, the first being that the objective is inherently controversial and that the spread in the data is due to this controversial aspect, or the second interpretation being that the objective is defined in such a manner that any number of people can derive a different meaning from the same statement. This was tested by investigating how the average geometric variance changed by applying consistency index thresholds of 20%, 15%, and 10%, i.e., all respondents with a consistency index above the threshold were omitted from the analysis. The results have been tabulated in Appendix F. Since the average geometric variance decreased for 25 of the 28 objectives at the 10% consistency index threshold, it was concluded that ill-defined definitions were probably the cause for the large variances. Additionally, this interpretation was chosen since it is the only one that can be controlled. As such, all objectives were reevaluated with special attention paid to those with the highest average geometric variances.

### 4.3.3 Revised Objectives

It was clear that the objectives needed to be refined so that they were unambiguous, comprehensive, direct, operational and understandable. After consulting two
Table 6. Average Geometric Variance for each Objective

<table>
<thead>
<tr>
<th>Hierarchy</th>
<th>Objective</th>
<th>( \sigma_g^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benefits</td>
<td>Disposition Flexibility</td>
<td>3.93</td>
</tr>
<tr>
<td></td>
<td>Fuel Requirement Reduction</td>
<td>3.01</td>
</tr>
<tr>
<td></td>
<td>Infrastructure Development</td>
<td>2.80</td>
</tr>
<tr>
<td></td>
<td>Legal Resolution</td>
<td>5.62</td>
</tr>
<tr>
<td></td>
<td>Local Improvements</td>
<td>4.01</td>
</tr>
<tr>
<td></td>
<td>Nuclear Political Stability</td>
<td>5.16</td>
</tr>
<tr>
<td></td>
<td>Pollution &amp; Emissions Reduction</td>
<td>5.35</td>
</tr>
<tr>
<td>Costs</td>
<td>Facility Construction &amp; Maintenance</td>
<td>4.17</td>
</tr>
<tr>
<td></td>
<td>Infrastructure Development</td>
<td>3.63</td>
</tr>
<tr>
<td></td>
<td>Legal Fees &amp; Fines</td>
<td>3.05</td>
</tr>
<tr>
<td></td>
<td>Licensing</td>
<td>3.70</td>
</tr>
<tr>
<td></td>
<td>Proliferation Prevention</td>
<td>4.01</td>
</tr>
<tr>
<td></td>
<td>Transportation</td>
<td>3.66</td>
</tr>
<tr>
<td></td>
<td>Waste Amount</td>
<td>3.79</td>
</tr>
<tr>
<td>Opportunities</td>
<td>American Nuclear Development</td>
<td>3.20</td>
</tr>
<tr>
<td></td>
<td>Decommissioning Allowance</td>
<td>1.84</td>
</tr>
<tr>
<td></td>
<td>Energy Policy Leadership</td>
<td>3.80</td>
</tr>
<tr>
<td></td>
<td>Long-term Energy Security</td>
<td>3.93</td>
</tr>
<tr>
<td></td>
<td>Promote Nuclear Industry</td>
<td>3.17</td>
</tr>
<tr>
<td></td>
<td>Technology Development</td>
<td>3.92</td>
</tr>
<tr>
<td></td>
<td>U.S. Government Competence</td>
<td>3.85</td>
</tr>
<tr>
<td>Risks</td>
<td>Feasibility</td>
<td>8.20</td>
</tr>
<tr>
<td></td>
<td>Potential Future Burden</td>
<td>5.23</td>
</tr>
<tr>
<td></td>
<td>Proliferation Potential</td>
<td>4.38</td>
</tr>
<tr>
<td></td>
<td>Public Perception</td>
<td>6.63</td>
</tr>
<tr>
<td></td>
<td>Radiotoxicity</td>
<td>3.90</td>
</tr>
<tr>
<td></td>
<td>Supply Availability</td>
<td>4.30</td>
</tr>
<tr>
<td></td>
<td>Waste Escape Accidents</td>
<td>5.66</td>
</tr>
</tbody>
</table>
external environmental and two external nuclear experts the following revised objectives were decided upon.

In addition to extensively revising the definitions of the objectives, the labels for each definition were also changed. These objective label changes can be seen in Table 7.

4.3.3.1 Benefits

The revised definitions for the benefits objectives were changed as 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 entailed no loss of meaning. Secondly, the definition was expanded so that it was 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 make clearer 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.
Table 7. Change in Objective Labels

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

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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 objective 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 objectives much more understandable and comprehensive.

The objective *Nuclear Political Stability* was removed since it was concluded that this concept was already adequately accounted for in the opportunities hierarchy. Additionally, the objective *Pollution and Emissions Reduction* was expunged completely since it was determined that this objective 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 objectives were derived for the benefits objective, the first being *Public and 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.
4.3.3.2 Costs

The definitions for the costs objectives were changed to the following: *Facility Construction and Maintenance* was changed to *Facility Construction, Operation, and 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 objective more comprehensive.

The definition of *Legal Fees and 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 objective 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 objective is more understandable and less vague.

*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, and Maintenance* objective and to make the objective more comprehensive.
The definition of *Transportation* was slightly altered to: 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 objective more comprehensive.

The objective *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 objective 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.

### 4.3.3.3 Opportunities

The definitions for the opportunities objectives were changed in the following ways: *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 objective 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 objective 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 to make the objective more understandable by what is meant by leadership in the realm of energy policy.

The objective *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 objective less ambiguous, specifically that the scope of nuclear is within electricity production and not to energy as a whole.

The objective 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 objective 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 objective more comprehensive and more understandable. Especially, that the objective goal 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 objective much less ambiguous and specify specifically what is meant by ‘competence.’

The objective 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 objective would not be largely differentiating between fuel cycles. With these revisions it was concluded that the opportunities hierarchy was complete.
4.3.3.4 Risks

The definitions of the risks objectives were changed as follows: The objective 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 objective 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 objective was more understandable and so that ambiguity would again be diminished.

The objective *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 objective *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 objective can be broken down further into the exposure to just site-workers and the exposure to just members of the general public when further clarity is required.

The definition of \textit{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 objective 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 objective \textit{Feasibility} was changed to \textit{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 revised hierarchy of all objectives can be seen in Figure 8.

It was with a certain amount of confidence that these objectives were utilized and a full evaluation was undertaken based on AHP principles. The full evaluation of these objectives can be found in Ch. 6. Presented next, in Ch. 5, is the evaluation of subject matter experts relevant to the selection of a nuclear fuel cycle.
Fig. 8. Hierarchy after Revision
CHAPTER 5

SUBJECT MATTER EXPERT EVALUATION

It was predicted that simply using the derived weights on objectives 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 would not be 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 previously mentioned objectives, they would also evaluate the qualifications of relevant subject matter experts. The relevant subject matter experts were Economists, Environmental Scientists, Nuclear Engineers and Scientists, and Political Scientists. Additionally, the general public would evaluate their own qualifications against the previously mentioned subject matter experts to derive a weight for their collective preferences. From these comparisons each group of subject matter experts can have their objective weights weighted by how the general public views them as qualified.

To perform a more complete analysis the qualifications of the subject matter experts were evaluated three separate ways. Additionally, a multi-scale ranking was conducted to measure not only qualifications, but also the honesty, accessibility, and understandability of the different subject matter experts.

5.1 Survey Methodology

5.1.1 Survey: AHP Subject Matter Experts

Two surveys were conducted. The first followed an AHP approach, where each respondent was initially given an list of the five subject matter experts in a random
order, with definitions next to their titles. See Appendix M for a copy of this survey. The given titles and definitions of the subject matter experts were as follows:

- **Economists**: Experts in the study of how individuals and groups make decisions about how to utilize limited resources to best satisfy their wants, needs, and desires.

- **Environmental Scientists**: Experts in the science that studies interactions between the physical, chemical, and biological components of the environment, including their effects on all types of organisms, but more often refers to human impact on the environment.

- **Nuclear Engineers & Scientists**: Experts in the branch of engineering that takes advantage of the atomic and nuclear properties of matter for the development of technologies and applications that benefit humankind (electricity, medical applications, industrial applications).

- **Political Scientists**: Experts in the social science that studies the policies and processes associated with the government of local, state, nation, and multinational institutions.

- **The General Public**: Any concerned individual who is not necessarily a member of the other mentioned groups.

The first question in the first survey was given as “Please rank these groups from the most qualified (1) to the least qualified (5) in terms of selecting a method of used nuclear fuel disposal for the United States.” The respondent was then able to graphically change the position of the group from better or worse. This first question served two purposes. The first was to see what the qualification weights of experts would be from a simple ranking. The second was in the context of AHP, that having the respondents first order their preferences will tend to lead to much
better consistency results when performing the pairwise comparisons [9]. The second question in the first survey was a matrix of pairwise comparisons, the kind that would be used in any AHP approach. The question asked was:

“Finally, please compare each group against each other group with respect to who would be more qualified in selecting a method of used nuclear fuel disposal for the United States, and then by selecting how much more qualified that group is over the other group. If the groups are equally qualified, simply put equal. If equal, when asked “How much more qualified?” please select “N/A (choices are equal)” . As a reminder, the descriptions of the various groups are included below.”

The questions were randomized so that the pairwise comparisons appeared in a random order. Two questions were asked for each pair, “Which one is more qualified?” to which the respondent could either reply A, B, or Equal, and then “How much more qualified?” to which the respondent could reply Slightly, Moderately, Strongly, Very Strongly, Extremely, or N/A (choices are equal). For this survey there were a total of 10 pairwise comparisons. There was one additional question on each respondent’s preference for nuclear power as an energy source for the U.S. and an additional six demographic questions.

Two samples were purchased from an internet-based electronic survey company. The first was a sample size of 50, with the only limiting criterion being that the respondents needed to be registered voters. After this survey was complete, an additional sample size of 50 was purchased to balance out the racial demographics with the same limiting criterion of being registered voters.
5.1.2 Survey: Multi-scale Rating Subject Matter Experts

The second survey asked respondents to evaluate the same subject matter experts on four different scales, Qualifications, Honesty, Accessibility, and Understandability, see Appendix N for a copy of the survey.

The first question in this survey asked the respondents to “Indicate your preferences for the following energy sources to generate electricity in the future.” and listed the following energy sources Wind, Natural Gas, Nuclear, Water (Hydroelectric), Coal, and Solar. This question was included to try to get the respondents thinking about nuclear power and energy sources in general.

The next four questions were about the multi-scale ranking and followed the form “How (blank) are each of the following information sources for nuclear waste disposal information?” In the location of (blank) in the preceding question was either qualified (credentials, competence, etc.), honest (unbiased, trustworthy, etc), accessible (readily available and obtainable), or understandable (easily understood by the general public). The possible responses for each question all followed the same format, and for the qualified question were as follows: Not Qualified at All, A Little Bit Qualified, Somewhat Qualified, Qualified, and Very Qualified. For this survey no elaborative definitions were given for the subject matter experts, as it was thought that perhaps these definitions could bias the respondents. The final questions on this survey were demographic, and included an opportunity for the respondent to share their thoughts on nuclear energy or energy sources in general.

A sample size of 400 respondents was purchased from the same internet-based electronic survey company; with the limiting criteria of: registered voter and nationally representative racial, gender, regional, and age demographics.
5.2 Survey Collection Abandonment Rates

The collection of both surveys went smoothly with each only having an average abandonment rate of 17%. This means that of everyone who started either survey, 83% eventually completed them. This abandonment rate was considered normal by the internet-based electronic survey company and the collection of the surveys went uninterrupted.

5.3 Results of Subject Matter Expert Surveys

5.3.1 Qualification Weights: Simple Ranking

The collected sample size for the first survey was 104, and the frequency table of the responses for each ranking is shown in Appendix G in Table 54. For the sake of generating weights it was necessary to interpret the rankings into numerical values. The following scheme was used: Rank 1 = 4, Rank 2 = 3, Rank 3 = 2, Rank 4 = 1, and Rank 5 = 0. The frequency was multiplied by the value and summed for each subject matter expert. Dividing by the sample size gave the mean value for each group. Additionally, the standard deviation was found for each group using the interpretation scheme. In order to generate weights, the mean values were normalized by the sum of all mean values. To find the standard deviation in normalized-weight form, the standard deviations were normalized by the sum of all mean values. These results can be seen numerically in Table 8 and graphically in Figure 9.
Table 8. Weights Table of Subject Matter Experts for Simple Ranking

<table>
<thead>
<tr>
<th>Subject Matter Expert</th>
<th>Weight</th>
<th>Weight SD</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental Scientists</td>
<td>33.27%</td>
<td>8.86%</td>
<td>3.33</td>
<td>0.89</td>
</tr>
<tr>
<td>Nuclear Engineers &amp; Scientists</td>
<td>31.83%</td>
<td>9.43%</td>
<td>3.18</td>
<td>0.94</td>
</tr>
<tr>
<td>Economists</td>
<td>13.94%</td>
<td>8.64%</td>
<td>1.39</td>
<td>0.86</td>
</tr>
<tr>
<td>Political Scientists</td>
<td>11.63%</td>
<td>9.04%</td>
<td>1.16</td>
<td>0.90</td>
</tr>
<tr>
<td>The General Public</td>
<td>9.33%</td>
<td>12.01%</td>
<td>0.93</td>
<td>1.20</td>
</tr>
</tbody>
</table>

Fig. 9. Weight of Subject Matter Experts through Simple Ranking Technique Including One Standard Deviation Above and Below the Mean
5.3.1.1   Statistical Significance Testing

To investigate the significance of the difference in the means, not the weights, for each subject matter expert group, a Wilcoxon Signed Ranks Test was run comparing each group to every other group with the statistical software SPSS. The results are listed in Table 9. The table is set up such that subject matter expert 1 has a larger mean than subject matter expert 2 and their means including their variances are being compared to each other. The Z Score represents the number of standard deviations of difference between the means taking the variance and the sample size into account. The final column represents the significance of the difference in the means and is the standard $p$ value used in statistics, e.g., if $p < 0.05$, then we can say that there is a difference between the means at a 95% confidence level. For these results, the only occasions where there are not significant differences in the means of two groups at the 95% confidence level are when comparing environmental scientists to nuclear engineers and scientists, economists to political scientists, and political scientists to the general public. Put another way, the means of these groups are close enough that the difference between them is not significant.
Table 9. Statistical Comparison of Means of SME using Simple Ranking for Significant Differences with Wilcoxon Signed Ranks Test

<table>
<thead>
<tr>
<th>Subject Matter Expert 1</th>
<th>Subject Matter Expert 2</th>
<th>Z Score</th>
<th>Sig. (p=)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental Scientists</td>
<td>Nuclear Engineers &amp; Scientists</td>
<td>1.247</td>
<td>0.213</td>
</tr>
<tr>
<td>Environmental Scientists</td>
<td>Economists</td>
<td>8.015</td>
<td>0.000</td>
</tr>
<tr>
<td>Environmental Scientists</td>
<td>Political Scientists</td>
<td>8.176</td>
<td>0.000</td>
</tr>
<tr>
<td>Environmental Scientists</td>
<td>The General Public</td>
<td>8.072</td>
<td>0.000</td>
</tr>
<tr>
<td>Nuclear Engineers &amp; Scientists</td>
<td>Economists</td>
<td>8.109</td>
<td>0.000</td>
</tr>
<tr>
<td>Nuclear Engineers &amp; Scientists</td>
<td>Political Scientists</td>
<td>8.002</td>
<td>0.000</td>
</tr>
<tr>
<td>Nuclear Engineers &amp; Scientists</td>
<td>The General Public</td>
<td>7.326</td>
<td>0.000</td>
</tr>
<tr>
<td>Economists</td>
<td>Political Scientists</td>
<td>1.834</td>
<td>0.067</td>
</tr>
<tr>
<td>Economists</td>
<td>The General Public</td>
<td>2.785</td>
<td>0.005</td>
</tr>
<tr>
<td>Political Scientists</td>
<td>The General Public</td>
<td>1.426</td>
<td>0.154</td>
</tr>
</tbody>
</table>
5.3.2 Qualification Weights: AHP Method

In addition to the previous method of developing weights, AHP was used. Although the 104 respondents completed the relatively easy task of ranking the subject matter experts, four failed to complete the entirety of the pairwise comparisons and the sample size was reduced to 100. With the numerical interpretation scheme shown in Table 10. Three separate analyses were done, one for each scale: integer, balanced, and power.

<table>
<thead>
<tr>
<th>How Much More Important?</th>
<th>Integer</th>
<th>Balanced</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equally Important</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Slightly</td>
<td>2</td>
<td>1.22</td>
<td>1.32</td>
</tr>
<tr>
<td>Moderately</td>
<td>3</td>
<td>1.50</td>
<td>1.73</td>
</tr>
<tr>
<td>Strongly</td>
<td>5</td>
<td>2.33</td>
<td>3</td>
</tr>
<tr>
<td>Very Strongly</td>
<td>7</td>
<td>4</td>
<td>5.20</td>
</tr>
<tr>
<td>Extremely</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
</tbody>
</table>

A code was written to evaluate all 100 responses under each numerical interpretation scheme, and to subsequently derive the weights for each expert group from each respondent as well as each respondent’s consistency index, i.e., the level of inconsistency in their responses. After each respondent’s weights were derived, the arithmetic mean and the normalized geometric mean were used to get weight values. Additionally, to find the spread of the data the arithmetic standard deviation was used and the geometric standard deviation was used. See Appendix D for a full discussion on both geometric and arithmetic means and their respective standard deviations.

When using the arithmetic mean of each respondent’s weights for the different subject matter experts, the sum of the arithmetic means would equal 100% and no
further scaling was required to generate the final weight values. When using the geometric mean of each respondent’s weights for the different subject matter experts, the sum of the geometric means would not equal 100% and so the geometric mean of each subject matter expert’s weight was normalized over the sum of all subject matter expert’s geometric means.

Additionally, the effect of inconsistency was evaluated by performing the analysis at four different consistency index thresholds. The first, or no threshold, included the weights from all participants regardless of their consistency index. The second was a 20% consistency index threshold, i.e., respondents with consistency indexes greater than 20% were removed from the analysis. Likewise, the third and forth thresholds were for greater than 15% and 10% consistency indexes, respectively.

5.3.2.1 Rates of Reduction for AHP Method

Applying the different consistency index thresholds affected the sample sizes for the AHP evaluation of the subject matter experts. The effect of these thresholds can be seen in Table 11. Additionally, for the figures and tables in the subsequent section, the sample size of the results are from the 10% inconsistency threshold column, i.e., Subject Matter Experts has a sample size of 54.

Table 11. Effect of Inconsistency Threshold on Sample Sizes of Surveys Collected from the General Public for Subject Matter Experts with Integer Scale

<table>
<thead>
<tr>
<th>Hierarchy</th>
<th>Sample Size</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No Threshold</td>
</tr>
<tr>
<td>Subject Matter Experts</td>
<td>100</td>
</tr>
</tbody>
</table>
5.3.2.2 AHP Results

The different weights and sample sizes for each numerical interpretation scheme and for no consistency index threshold and for 10% consistency index threshold have been tabulated in Appendices I through K. Presented in Table 12 are the values of the arithmetic mean, denoted ‘A. Weight’, and its standard deviation, denoted ‘A. Weight SD’, along with the geometric mean, denoted ‘G. Weight’ and the geometric standard deviation, denoted ‘G. Weight SD’ under the integer numerical interpretation at the 10% consistency index threshold. Note that while the arithmetic distribution can be described by *adding* or *subtracting* the standard deviation to or from the mean, the geometric distribution is described by *multiplying* or *dividing* the mean by the standard deviation. These results can be seen graphically in Figure 10; the results are organized based on the arithmetic mean and include one standard deviation above and below the mean weight.

Table 12. Weights Table of Subject Matter Experts for AHP using Integer Scale at 10% Consistency Index Threshold

<table>
<thead>
<tr>
<th>Subject Matter Expert</th>
<th>A. Weight</th>
<th>A. Weight SD</th>
<th>G. Weight</th>
<th>G. Weight SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear Engineers &amp; Scientists</td>
<td>36.79%</td>
<td>13.01%</td>
<td>37.82%</td>
<td>1.49</td>
</tr>
<tr>
<td>Environmental Scientists</td>
<td>36.58%</td>
<td>12.43%</td>
<td>37.80%</td>
<td>1.46</td>
</tr>
<tr>
<td>Economists</td>
<td>9.55%</td>
<td>6.34%</td>
<td>8.83%</td>
<td>1.77</td>
</tr>
<tr>
<td>Political Scientists</td>
<td>9.44%</td>
<td>7.16%</td>
<td>8.62%</td>
<td>1.77</td>
</tr>
<tr>
<td>The General Public</td>
<td>7.64%</td>
<td>5.79%</td>
<td>6.93%</td>
<td>1.79</td>
</tr>
</tbody>
</table>
Fig. 10. Arithmetic and Geometric Weights of Subject Matter Experts Including 1 Standard Deviation Above and Below Mean using Integer Scale at 10% Consistency Index Threshold
5.3.2.3 Statistical Significance Testing

To investigate the significance of the difference in the weights, not the means, for each subject matter expert group, a Wilcoxon Signed Ranks Test was run comparing each group to every other group with the statistical software SPSS. The results are listed in Table 13. The table is set up such that subject matter expert 1 has a larger weight than subject matter expert 2 and their weights including their arithmetic variances are being compared to each other. For these results, the only occasions where there are not significant differences in the weights of two groups at the 95% confidence level are when comparing nuclear engineers and scientists to environmental scientists, economists to political scientists, and political scientists to the general public. Put another way, the weights of these groups are close enough that the difference between them is not significant.

Table 13. Statistical Comparison of Weights of SME using AHP for Significant Differences with Wilcoxon Signed Ranks Test

<table>
<thead>
<tr>
<th>Subject Matter Expert 1</th>
<th>Subject Matter Expert 2</th>
<th>Z Score</th>
<th>Sig. ($p =$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear Engineers &amp; Scientists</td>
<td>Environmental Scientists</td>
<td>0.031</td>
<td>0.975</td>
</tr>
<tr>
<td>Nuclear Engineers &amp; Scientists</td>
<td>Economists</td>
<td>6.033</td>
<td>0.000</td>
</tr>
<tr>
<td>Nuclear Engineers &amp; Scientists</td>
<td>Political Scientists</td>
<td>5.834</td>
<td>0.000</td>
</tr>
<tr>
<td>Nuclear Engineers &amp; Scientists</td>
<td>The General Public</td>
<td>6.048</td>
<td>0.000</td>
</tr>
<tr>
<td>Environmental Scientists</td>
<td>Economists</td>
<td>6.053</td>
<td>0.000</td>
</tr>
<tr>
<td>Environmental Scientists</td>
<td>Political Scientists</td>
<td>5.884</td>
<td>0.000</td>
</tr>
<tr>
<td>Environmental Scientists</td>
<td>The General Public</td>
<td>6.154</td>
<td>0.000</td>
</tr>
<tr>
<td>Economists</td>
<td>Political Scientists</td>
<td>0.457</td>
<td>0.648</td>
</tr>
<tr>
<td>Economists</td>
<td>The General Public</td>
<td>2.371</td>
<td>0.018</td>
</tr>
<tr>
<td>Political Scientists</td>
<td>The General Public</td>
<td>1.835</td>
<td>0.066</td>
</tr>
</tbody>
</table>
5.3.3 Qualification Weights: Direct Valuations

Although a sample size of 400 was purchased, the total number of respondents ended up being 496. These additional respondents were provided to balance all demographic data. The frequency tables for each question are presented in Appendix G beside the numerical interpretation of each response. Qualifications is Table 55, Honesty is Table 56, Accessibility is Table 57, and Understandability is Table 58.

Similar to the case of the simple ranking, the process of generating weights required interpreting the verbal responses into numerical values. A similar 0, 1, 2, 3, 4 numerical interpretation scheme was used and this interpretation scheme is shown in Table 14. The frequency was multiplied by the value and summed for each subject matter expert. Dividing by the sample size gave the mean value for each group. Additionally, the standard deviation was found for each group using the interpretation scheme. In order to generate weights, the mean values were normalized by the sum of all mean values. To find the standard deviation in normalized-weight form, the standard deviations were normalized by the sum of all mean values. These results for qualifications can be seen in Table 15. Similarly, the numerical results for Honesty, Accessibility, and Understandability can be found in Tables 17, 19, and 21, respectively. These results can be seen graphically in Figures 11 through 14.
### Table 14. Numerical Interpretation of Verbal Response for each Question

<table>
<thead>
<tr>
<th>Value</th>
<th>Qualified</th>
<th>Honest</th>
<th>Accessible</th>
<th>Understandable</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Not Qualified at All</td>
<td>Not Honest at All</td>
<td>Not Accessible at All</td>
<td>Not Understandable at All</td>
</tr>
<tr>
<td>1</td>
<td>A Little Bit Qualified</td>
<td>A Little Bit Honest</td>
<td>A Little Bit Accessible</td>
<td>A Little Bit Understandable</td>
</tr>
<tr>
<td>2</td>
<td>Somewhat Qualified</td>
<td>Somewhat Honest</td>
<td>Somewhat Accessible</td>
<td>Somewhat Understandable</td>
</tr>
<tr>
<td>3</td>
<td>Qualified</td>
<td>Honest</td>
<td>Accessible</td>
<td>Understandable</td>
</tr>
<tr>
<td>4</td>
<td>Very Qualified</td>
<td>Very Honest</td>
<td>Very Accessible</td>
<td>Very Understandable</td>
</tr>
</tbody>
</table>
5.3.3.1 Qualifications Results and Statistical Significance

<table>
<thead>
<tr>
<th>Subject Matter Expert</th>
<th>Weight</th>
<th>Weight SD</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear Engineers &amp; Scientists</td>
<td>38.43%</td>
<td>11.51%</td>
<td>3.27</td>
<td>0.98</td>
</tr>
<tr>
<td>Environmental Scientists</td>
<td>35.37%</td>
<td>12.33%</td>
<td>3.00</td>
<td>1.05</td>
</tr>
<tr>
<td>Economists</td>
<td>11.13%</td>
<td>13.04%</td>
<td>0.95</td>
<td>1.11</td>
</tr>
<tr>
<td>Political Scientists</td>
<td>9.11%</td>
<td>11.56%</td>
<td>0.78</td>
<td>0.98</td>
</tr>
<tr>
<td>The General Public</td>
<td>5.95%</td>
<td>9.38%</td>
<td>0.51</td>
<td>0.80</td>
</tr>
</tbody>
</table>

Fig. 11. Qualification Weights of Subject Matter Experts through Direct Preference Including One Standard Deviation Above and Below the Mean
To investigate the significance of the difference in the qualification means, not the weights, for each subject matter expert group, a Wilcoxon Signed Ranks Test was run comparing each group to every other group with the statistical software SPSS. The results are listed in Table 16. The table is set up such that subject matter expert 1 has a larger mean than subject matter expert 2 and their means including their variances are being compared to each other. For these results, the means of each group is statistically significantly different from every other group; this result is aided by the large sample size of 496.

Table 16. Statistical Comparison of Means of Qualifications for SME using Direct Valuations for Significant Differences with Wilcoxon Signed Ranks Test

<table>
<thead>
<tr>
<th>Subject Matter Expert 1</th>
<th>Subject Matter Expert 2</th>
<th>Z Score</th>
<th>Sig. (p=)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear Engineers &amp; Scientists</td>
<td>Environmental Scientists</td>
<td>6.176</td>
<td>0.000</td>
</tr>
<tr>
<td>Nuclear Engineers &amp; Scientists</td>
<td>Economists</td>
<td>17.856</td>
<td>0.000</td>
</tr>
<tr>
<td>Nuclear Engineers &amp; Scientists</td>
<td>Political Scientists</td>
<td>18.150</td>
<td>0.000</td>
</tr>
<tr>
<td>Nuclear Engineers &amp; Scientists</td>
<td>The General Public</td>
<td>18.640</td>
<td>0.000</td>
</tr>
<tr>
<td>Environmental Scientists</td>
<td>Economists</td>
<td>17.663</td>
<td>0.000</td>
</tr>
<tr>
<td>Environmental Scientists</td>
<td>Political Scientists</td>
<td>17.915</td>
<td>0.000</td>
</tr>
<tr>
<td>Environmental Scientists</td>
<td>The General Public</td>
<td>18.394</td>
<td>0.000</td>
</tr>
<tr>
<td>Economists</td>
<td>Political Scientists</td>
<td>3.687</td>
<td>0.000</td>
</tr>
<tr>
<td>Economists</td>
<td>The General Public</td>
<td>8.537</td>
<td>0.000</td>
</tr>
<tr>
<td>Political Scientists</td>
<td>The General Public</td>
<td>6.286</td>
<td>0.000</td>
</tr>
</tbody>
</table>
5.3.3.2 Honesty Results and Statistical Significance

Table 17. Weights Table of Subject Matter Experts for Honesty

<table>
<thead>
<tr>
<th>Subject Matter Expert</th>
<th>Weight Mean</th>
<th>Weight SD</th>
<th>Mean SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental Scientists</td>
<td>29.56%</td>
<td>13.08%</td>
<td>2.55</td>
</tr>
<tr>
<td>Nuclear Engineers &amp; Scientists</td>
<td>28.88%</td>
<td>12.34%</td>
<td>2.51</td>
</tr>
<tr>
<td>Economists</td>
<td>16.29%</td>
<td>12.24%</td>
<td>1.40</td>
</tr>
<tr>
<td>The General Public</td>
<td>14.82%</td>
<td>12.09%</td>
<td>1.28</td>
</tr>
<tr>
<td>Political Scientists</td>
<td>10.45%</td>
<td>11.38%</td>
<td>0.91</td>
</tr>
</tbody>
</table>

Fig. 12. Honesty Weights of Subject Matter Experts through Direct Preference Including One Standard Deviation Above and Below the Mean
To investigate the significance of the difference in the honesty means, not the weights, for each subject matter expert group, a Wilcoxon Signed Ranks Test was run comparing each group to every other group with the statistical software SPSS. The results are listed in Table 18. The table is set up such that subject matter expert 1 has a larger mean than subject matter expert 2 and their means including their variances are being compared to each other. For these results, the only occasion where there is not a significant difference in the means of two groups at the 95% confidence level is when comparing environmental scientists to nuclear engineers and scientists.

Table 18. Statistical Comparison of Means of Honesty for SME using Direct Valuations for Significant Differences with Wilcoxon Signed Ranks Test

<table>
<thead>
<tr>
<th>Subject Matter Expert 1</th>
<th>Subject Matter Expert 2</th>
<th>Z Score</th>
<th>Sig. (p=)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental Scientists</td>
<td>Nuclear Engineers &amp; Scientists</td>
<td>1.159</td>
<td>0.247</td>
</tr>
<tr>
<td>Environmental Scientists</td>
<td>Economists</td>
<td>14.458</td>
<td>0.000</td>
</tr>
<tr>
<td>Environmental Scientists</td>
<td>The General Public</td>
<td>14.347</td>
<td>0.000</td>
</tr>
<tr>
<td>Environmental Scientists</td>
<td>Political Scientists</td>
<td>16.680</td>
<td>0.000</td>
</tr>
<tr>
<td>Nuclear Engineers &amp; Scientists</td>
<td>Economists</td>
<td>13.864</td>
<td>0.000</td>
</tr>
<tr>
<td>Nuclear Engineers &amp; Scientists</td>
<td>The General Public</td>
<td>14.029</td>
<td>0.000</td>
</tr>
<tr>
<td>Nuclear Engineers &amp; Scientists</td>
<td>Political Scientists</td>
<td>16.397</td>
<td>0.000</td>
</tr>
<tr>
<td>Economists</td>
<td>The General Public</td>
<td>2.347</td>
<td>0.019</td>
</tr>
<tr>
<td>Economists</td>
<td>Political Scientists</td>
<td>9.456</td>
<td>0.000</td>
</tr>
<tr>
<td>The General Public</td>
<td>Political Scientists</td>
<td>7.177</td>
<td>0.000</td>
</tr>
</tbody>
</table>
5.3.3.3 Accessibility Results and Statistical Significance

Table 19. Weights Table of Subject Matter Experts for Accessibility

<table>
<thead>
<tr>
<th>Subject Matter Expert</th>
<th>Weight</th>
<th>Weight SD</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental Scientists</td>
<td>25.41%</td>
<td>12.66%</td>
<td>2.26</td>
<td>1.13</td>
</tr>
<tr>
<td>Nuclear Engineers &amp; Scientists</td>
<td>23.28%</td>
<td>13.03%</td>
<td>2.07</td>
<td>1.16</td>
</tr>
<tr>
<td>Political Scientists</td>
<td>17.95%</td>
<td>13.38%</td>
<td>1.60</td>
<td>1.19</td>
</tr>
<tr>
<td>Economists</td>
<td>16.82%</td>
<td>12.10%</td>
<td>1.49</td>
<td>1.08</td>
</tr>
<tr>
<td>The General Public</td>
<td>16.55%</td>
<td>14.24%</td>
<td>1.47</td>
<td>1.27</td>
</tr>
</tbody>
</table>

Fig. 13. Accessibility Weights of Subject Matter Experts through Direct Preference Including One Standard Deviation Above and Below the Mean
To investigate the significance of the difference in the accessibility means, not the weights, for each subject matter expert group, a Wilcoxon Signed Ranks Test was run comparing each group to every other group with the statistical software SPSS. The results are listed in Table 20. The table is set up such that subject matter expert 1 has a larger mean than subject matter expert 2 and their means including their variances are being compared to each other. For these results, the only occasion where there is not a significant difference in the means of two groups at the 95% confidence level is when comparing economists to the general public.

Table 20. Statistical Comparison of Means of Accessibility for SME using Direct Valuations for Significant Differences with Wilcoxon Signed Ranks Test

<table>
<thead>
<tr>
<th>Subject Matter Expert 1</th>
<th>Subject Matter Expert 2</th>
<th>Z Score</th>
<th>Sig. (p=)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental Scientists</td>
<td>Nuclear Engineers &amp; Scientists</td>
<td>4.567</td>
<td>0.000</td>
</tr>
<tr>
<td>Environmental Scientists</td>
<td>Political Scientists</td>
<td>9.919</td>
<td>0.000</td>
</tr>
<tr>
<td>Environmental Scientists</td>
<td>Economists</td>
<td>12.063</td>
<td>0.000</td>
</tr>
<tr>
<td>Environmental Scientists</td>
<td>The General Public</td>
<td>10.135</td>
<td>0.000</td>
</tr>
<tr>
<td>Nuclear Engineers &amp; Scientists</td>
<td>Political Scientists</td>
<td>6.894</td>
<td>0.000</td>
</tr>
<tr>
<td>Nuclear Engineers &amp; Scientists</td>
<td>Economists</td>
<td>8.814</td>
<td>0.000</td>
</tr>
<tr>
<td>Nuclear Engineers &amp; Scientists</td>
<td>The General Public</td>
<td>7.406</td>
<td>0.000</td>
</tr>
<tr>
<td>Political Scientists</td>
<td>Economists</td>
<td>2.031</td>
<td>0.042</td>
</tr>
<tr>
<td>Political Scientists</td>
<td>The General Public</td>
<td>2.465</td>
<td>0.014</td>
</tr>
<tr>
<td>Economists</td>
<td>The General Public</td>
<td>0.676</td>
<td>0.499</td>
</tr>
</tbody>
</table>
5.3.3.4 Understandability Results and Statistical Significance

Table 21. Weights Table of Subject Matter Experts for Understandability

<table>
<thead>
<tr>
<th>Subject Matter Expert</th>
<th>Weight</th>
<th>Weight SD</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental Scientists</td>
<td>25.14%</td>
<td>15.04%</td>
<td>1.85</td>
<td>1.11</td>
</tr>
<tr>
<td>Nuclear Engineers &amp; Scientists</td>
<td>21.88%</td>
<td>14.80%</td>
<td>1.62</td>
<td>1.09</td>
</tr>
<tr>
<td>The General Public</td>
<td>18.11%</td>
<td>15.40%</td>
<td>1.34</td>
<td>1.14</td>
</tr>
<tr>
<td>Political Scientists</td>
<td>17.45%</td>
<td>15.01%</td>
<td>1.28</td>
<td>1.11</td>
</tr>
<tr>
<td>Economists</td>
<td>17.42%</td>
<td>13.76%</td>
<td>1.28</td>
<td>1.01</td>
</tr>
</tbody>
</table>

Fig. 14. Understandability Weights of Subject Matter Experts through Direct Preference Including One Standard Deviation Above and Below the Mean
To investigate the significance of the difference in the understandability means, not the weights, for each subject matter expert group, a Wilcoxon Signed Ranks Test was run comparing each group to every other group with the statistical software SPSS. The results are listed in Table 22. The table is set up such that subject matter expert 1 has a larger mean than subject matter expert 2 and their means including their variances are being compared to each other. For these results, the only occasions where there are not significant differences in the means of two groups at the 95% confidence level are when comparing the general public to political scientists, the general public to economists, and political scientists to economists.

Table 22. Statistical Comparison of Means of Understandability for SME using Direct Valuations for Significant Differences with Wilcoxon Signed Ranks Test

<table>
<thead>
<tr>
<th>Subject Matter Expert 1</th>
<th>Subject Matter Expert 2</th>
<th>Z Score</th>
<th>Sig. (p=)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental Scientists</td>
<td>Nuclear Engineers &amp; Scientists</td>
<td>5.782</td>
<td>0.000</td>
</tr>
<tr>
<td>Environmental Scientists</td>
<td>The General Public</td>
<td>7.461</td>
<td>0.000</td>
</tr>
<tr>
<td>Environmental Scientists</td>
<td>Political Scientists</td>
<td>9.275</td>
<td>0.000</td>
</tr>
<tr>
<td>Environmental Scientists</td>
<td>Economists</td>
<td>10.429</td>
<td>0.000</td>
</tr>
<tr>
<td>Nuclear Engineers &amp; Scientists</td>
<td>The General Public</td>
<td>3.895</td>
<td>0.000</td>
</tr>
<tr>
<td>Nuclear Engineers &amp; Scientists</td>
<td>Political Scientists</td>
<td>5.737</td>
<td>0.000</td>
</tr>
<tr>
<td>Nuclear Engineers &amp; Scientists</td>
<td>Economists</td>
<td>6.210</td>
<td>0.000</td>
</tr>
<tr>
<td>The General Public</td>
<td>Political Scientists</td>
<td>1.549</td>
<td>0.121</td>
</tr>
<tr>
<td>The General Public</td>
<td>Economists</td>
<td>1.137</td>
<td>0.256</td>
</tr>
<tr>
<td>Political Scientists</td>
<td>Economists</td>
<td>-0.153</td>
<td>0.879</td>
</tr>
</tbody>
</table>
5.4 Discussion of Subject Matter Expert Results

In each method, similar results were obtained. Specifically, in terms of qualifications the general public view nuclear engineers and scientists as the most qualified. However, environmental scientists are often considered almost equally as qualified. Generally, economists and political scientists are viewed by the general to be about one-third to one-fourth as qualified as either nuclear engineers and scientists or environmental scientists. The general public views themselves as the least qualified, but only slightly behind economists and political scientists. These results are essentially consistent between all three evaluation methods, giving good confidence in using the weights derived from any evaluation method.

The multi-scale rating revealed more interesting results. Specifically, that although nuclear engineers and scientists and environmental scientists are considered much more qualified, mean values of 3.3 and 3.0, respectively, they both drop to an average value of around 2.5 for honesty, meaning between somewhat honest and honest. Furthermore, when accessibility is evaluated nuclear engineers and scientists drop further to an average value of about 2, meaning somewhat accessible, while environmental scientists are rated best in terms of accessibility, 2.2. Perhaps equally unsurprising and unfortunate is the evaluation of understandability. Every subject matter expert receives an average rating between 1.2 and 1.9, meaning each is between A little bit understandable and somewhat understandable. Environmental scientists do have the highest rating in the category of understandability at around 1.9.

5.5 Conclusion for Subject Matter Experts

The results from the multi-scale rating demonstrate a vital reason to include environmental scientists in any evaluation of a nuclear fuel cycle along with nuclear
engineers and scientists. Nuclear engineers and scientists are viewed to be as qualified and honest as environmental scientists. Environmental scientists are also viewed by the general public as being slightly more accessible and slightly more understandable when compared to nuclear engineers.

It is for these reasons that the main subject matter experts used in any nuclear fuel cycle selection program be equally both nuclear engineers and scientists and environmental scientists. The other expert groups may be included, but by including only nuclear engineers and scientists and environmental scientists about 74% of the qualification weights are accounted for. Thus an analysis may not necessitate the inclusion of the other groups from the general public’s perspective.
CHAPTER 6

AN AHP BASED EVALUATION

6.1 Outline of Evaluation

In order to evaluate of the model developed in Ch. 4 some additional steps needed to be taken. These steps are closely related to the methodology set out by Yi et al, with an exception being the ranking of the subject matter experts which is unique to this evaluation [15]. The subject matter experts were weighted as developed in Ch. 5.

The first step in this evaluation was to determine the weights of the branch elements in the hierarchy, e.g., the components of maximize benefits, minimize costs, maximize opportunities, and minimize risks. This was done by surveying members of the general public in AHP style pairwise comparisons for the importance of each objective in the different hierarchy branches. Once these were complete, the weights were derived using AHP for the objectives in terms of the general public’s view. This process can be repeated for the other subject matter experts to derive their weights as well.

Expert judgment can then be used to populate values of each objective value for every alternative nuclear fuel cycle and also to develop the value functions associated with each objective. From here the results can be synthesized and an optimal fuel cycle selected.
6.2 Survey Design

Four surveys were designed to meet this task of evaluating the different objectives. The survey for the evaluation of the benefits objectives can be found in Appendix O, the survey for costs objectives in Appendix P, the survey for opportunities objectives in Appendix Q, and the survey for risks objectives in Appendix R. These four separate surveys followed the same layout.

The first question for the benefits survey was a simple ranking question stating:

“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 for the United States.”

The opportunities survey had nearly the same wording with the exception being “...least important (6)...” since there were only 6 objectives in this hierarchy, and replacing the work ‘BENEFITS’ with ‘OPPORTUNITIES.’ The first question for the costs was phrased slightly differently in accordance with its meaning:

“Please rank the following criteria from the most important (1) to the least important (7) in terms of the COSTS that are developed from the selection of a given method for the disposal of used nuclear fuel in the US.”

The risks survey followed the exact same wording as the costs survey with the word ‘COSTS’ being replaced with ‘RISKS.’

This simple ranking question again served two purposes. The first was to see how what the importance weights of the objectives would be from a simple ranking. The second was in the context of AHP, in that having the respondents first order their
preferences will tend to lead to much better consistency results when performing the pairwise comparisons [9].

The second question in each survey was a matrix of pairwise comparisons as per the AHP approach. For the benefits survey the question asked was:

“Please select which criterion is more important in terms of the BENEFITS that can be derived from the selection of a method for the disposal of used nuclear fuel in the US, and then please select by how much. If the criteria are equally qualified, simply put equal. If equal, when asked “How much more important?” please select “N/A (choices are equal)”. As a reminder, the descriptions of the various criteria are included below.”

The other three surveys asked essentially the same question only varying in the same manners as they did for the first question.

The questions were randomized so that the pairwise comparisons appeared in a random order. Two questions were asked for each pair, “Which one is more important?” to which the respondent could either reply A, B, or Equal, and then “How much more important?” to which the respondent could reply Slightly, Moderately, Strongly, Very Strongly, Extremely, or N/A (choices are equal). Thus for the benefits, costs, and risks surveys 21 pairwise comparisons were required in each, and for the opportunities survey 15 pairwise comparisons were required.

There was one additional question on the respondent’s preference for nuclear power as an energy source for the U.S. and six demographic questions for the benefits, costs, and opportunities surveys. Unfortunately, the risks survey accidentally had its intended preference question for nuclear power as an energy source omitted; however, the six demographic questions were rightfully included.

Two samples were purchased from the same internet-based electronic survey
company for each survey. The first for each survey was a sample size of 50, with the only limiting criterion being that the respondents needed to be a registered voters. After these surveys were complete, an additional sample size of 50 for each survey was purchased to balance out the racial demographics with the same limiting criterion of being registered voters.

6.3 Survey Collection Abandonment Rates

The collection of these four surveys proved more difficult than first imagined, and much more difficult than the collection of the previous subject matter expert surveys. The average abandonment rates for each survey were high enough that the internet-based electronic survey company stopped the collection of both samples before their completion to suggest changes be made to the survey design. The suggested changes were to alter the matrix-style pairwise comparison questions somehow. As the raison d’être of AHP is to elicit preferences from pairwise comparisons, the questions were not altered and the collection of the samples was restarted. In some cases the abandonment rates continued to be high and the internet-based electronic survey company again stopped collection, and the remainder of the unfulfilled survey responses was reimbursed. It is for this reason that the final sample sizes of the surveys are not equal to 100.

The average abandonment rates for the surveys are listed in Table 23. The subject matter expert survey abandonment rates are included in this table for comparison. The average abandonment rate for the benefits, costs, opportunities and risks objective surveys were 43%, 49%, 48%, and 56%, respectively.
### Table 23. Average Abandonment Rates for each Survey

<table>
<thead>
<tr>
<th>Survey</th>
<th>Average Abandonment Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benefits</td>
<td>43%</td>
</tr>
<tr>
<td>Costs</td>
<td>49%</td>
</tr>
<tr>
<td>Opportunities</td>
<td>48%</td>
</tr>
<tr>
<td>Risks</td>
<td>56%</td>
</tr>
<tr>
<td>AHP Subject Matter Expert</td>
<td>17%</td>
</tr>
<tr>
<td>Multi-scale Subject Matter Expert</td>
<td>17%</td>
</tr>
</tbody>
</table>
6.4 Results for Objectives Through Simple Ranking

For the sake of generating weights it was again necessary to interpret the rankings into numerical values.

The following scheme was used for the benefits, costs, and risks surveys: \(\text{Rank 1} = 6, \text{Rank 2} = 5, \text{Rank 3} = 4, \text{Rank 4} = 3, \text{Rank 5} = 2, \text{Rank 6} = 1,\) and \(\text{Rank 7} = 0.\)

For the opportunities survey, because there were only six objectives, the following interpretation scheme was used: \(\text{Rank 1} = 5, \text{Rank 2} = 4, \text{Rank 3} = 3, \text{Rank 4} = 2, \text{Rank 5} = 1, \text{Rank 6} = 0.\)

The frequency was multiplied by the value and summed for each subject matter expert. Dividing by the sample size gave the mean value for each group. Additionally, the standard deviation was found for each group using the interpretation scheme.

In order to generate weights, the mean values were normalized by the sum of all mean values. To find the standard deviation in normalized-weight form, the standard deviations were normalized by the sum of all mean values.

6.4.1 Simple Ranking: Benefits

The collected sample size for the first question on the benefits survey was 93, and the frequency table of the responses for each ranking is shown in Appendix H in Table 59.

The weights were derived from this frequency table based on the interpretation scheme detailed in §6.4. The results for the benefits objectives can be seen numerically in Table 24 and graphically in Figure 15.
Table 24. Weights Table of Benefits Objectives for Simple Ranking

<table>
<thead>
<tr>
<th>Benefits Objective</th>
<th>Weight</th>
<th>Weight SD</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Requirement Reduction</td>
<td>18.28%</td>
<td>9.30%</td>
<td>3.84</td>
<td>1.95</td>
</tr>
<tr>
<td>Local Economic Development</td>
<td>15.77%</td>
<td>8.66%</td>
<td>3.31</td>
<td>1.82</td>
</tr>
<tr>
<td>Disposal Flexibility</td>
<td>15.62%</td>
<td>9.24%</td>
<td>3.28</td>
<td>1.94</td>
</tr>
<tr>
<td>Increase Technical Workforce</td>
<td>13.31%</td>
<td>9.64%</td>
<td>2.80</td>
<td>2.02</td>
</tr>
<tr>
<td>Public &amp; Political Acceptance</td>
<td>13.11%</td>
<td>9.87%</td>
<td>2.75</td>
<td>2.07</td>
</tr>
<tr>
<td>National Infrastructure Development</td>
<td>12.29%</td>
<td>9.11%</td>
<td>2.58</td>
<td>1.91</td>
</tr>
<tr>
<td>Legal Resolution</td>
<td>11.62%</td>
<td>9.38%</td>
<td>2.44</td>
<td>1.97</td>
</tr>
</tbody>
</table>

Fig. 15. Weights of Benefits Objectives through Simple Ranking Technique Including One Standard Deviation Above and Below the Mean
To investigate the significance of the difference in the means, not the weights, for each benefits objective, a Wilcoxon Signed Ranks Test was run comparing each benefits objective to every other benefits objective with the statistical software SPSS. The results are listed in Table 25. The table is set up such that benefits objective 1 has a larger mean than benefits objective 2 and their means including their variances are being compared to each other. The Z Score represents the number of standard deviations of difference between the means taking the variance and the sample size into account. The final column represents the significance of the difference in the means and is the standard p value used in statistics, e.g., if $p < 0.05$, then we can say that there is a difference between the means at a 95% confidence level. For these results, the majority of the comparisons demonstrate no significant difference between the means at the 95% confidence level. The cases that do demonstrate a statistically significant difference at the 95% confidence level are when comparing Fuel Requirement Reduction to Increase Technical Workforce, Public and Political Acceptance, National Infrastructure Development, or Legal Resolution, when comparing Local Economic Development to National Infrastructure Development or Legal Resolution, or when comparing Disposal Flexibility to National Infrastructure Development or Legal Resolution.
Table 25. Statistical Comparison of Means of Benefits Objectives using Simple Ranking for Significant Differences with Wilcoxon Signed Ranks Test

<table>
<thead>
<tr>
<th>Benefits Objective 1</th>
<th>Benefits Objective 2</th>
<th>Z Score</th>
<th>Sig. (p=)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Requirement Reduction</td>
<td>Local Economic Development</td>
<td>1.673</td>
<td>0.094</td>
</tr>
<tr>
<td>Fuel Requirement Reduction</td>
<td>Disposal Flexibility</td>
<td>1.875</td>
<td>0.061</td>
</tr>
<tr>
<td>Fuel Requirement Reduction</td>
<td>Increase Technical Workforce</td>
<td>3.071</td>
<td>0.002</td>
</tr>
<tr>
<td>Fuel Requirement Reduction</td>
<td>Public and Political Acceptance</td>
<td>3.363</td>
<td>0.001</td>
</tr>
<tr>
<td>Fuel Requirement Reduction</td>
<td>National Infrastructure Dev.</td>
<td>3.964</td>
<td>0.000</td>
</tr>
<tr>
<td>Fuel Requirement Reduction</td>
<td>Legal Resolution</td>
<td>3.905</td>
<td>0.000</td>
</tr>
<tr>
<td>Local Economic Development</td>
<td>Disposal Flexibility</td>
<td>0.147</td>
<td>0.883</td>
</tr>
<tr>
<td>Local Economic Development</td>
<td>Increase Technical Workforce</td>
<td>1.620</td>
<td>0.105</td>
</tr>
<tr>
<td>Local Economic Development</td>
<td>Public and Political Acceptance</td>
<td>1.600</td>
<td>0.109</td>
</tr>
<tr>
<td>Local Economic Development</td>
<td>National Infrastructure Dev.</td>
<td>2.427</td>
<td>0.015</td>
</tr>
<tr>
<td>Local Economic Development</td>
<td>Legal Resolution</td>
<td>2.941</td>
<td>0.003</td>
</tr>
<tr>
<td>Disposal Flexibility</td>
<td>Increase Technical Workforce</td>
<td>1.385</td>
<td>0.166</td>
</tr>
<tr>
<td>Disposal Flexibility</td>
<td>Public and Political Acceptance</td>
<td>1.729</td>
<td>0.084</td>
</tr>
<tr>
<td>Disposal Flexibility</td>
<td>National Infrastructure Dev.</td>
<td>2.268</td>
<td>0.023</td>
</tr>
<tr>
<td>Disposal Flexibility</td>
<td>Legal Resolution</td>
<td>2.719</td>
<td>0.007</td>
</tr>
<tr>
<td>Increase Technical Workforce</td>
<td>Public and Political Acceptance</td>
<td>0.085</td>
<td>0.933</td>
</tr>
<tr>
<td>Increase Technical Workforce</td>
<td>National Infrastructure Dev.</td>
<td>0.541</td>
<td>0.588</td>
</tr>
<tr>
<td>Increase Technical Workforce</td>
<td>Legal Resolution</td>
<td>1.063</td>
<td>0.288</td>
</tr>
<tr>
<td>Public and Political Acceptance</td>
<td>National Infrastructure Dev.</td>
<td>0.439</td>
<td>0.661</td>
</tr>
<tr>
<td>Public and Political Acceptance</td>
<td>Legal Resolution</td>
<td>1.098</td>
<td>0.272</td>
</tr>
<tr>
<td>National Infrastructure Dev.</td>
<td>Legal Resolution</td>
<td>0.453</td>
<td>0.651</td>
</tr>
</tbody>
</table>
6.4.2 Simple Ranking: Costs

The collected sample size for the first question on the costs survey was 70, and the frequency table of the responses for each ranking is shown in Appendix H in Table 60.

The weights were derived from this frequency table based on the interpretation scheme detailed in §6.4. The results for the costs objectives can be seen numerically in Table 26 and graphically in Figure 16.

<table>
<thead>
<tr>
<th>Costs Objective</th>
<th>Weight</th>
<th>Weight SD</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facility Construction, Operation, &amp; Maintenance</td>
<td>18.44%</td>
<td>9.35%</td>
<td>3.87</td>
<td>1.96</td>
</tr>
<tr>
<td>Proliferation Prevention</td>
<td>18.37%</td>
<td>9.50%</td>
<td>3.86</td>
<td>1.99</td>
</tr>
<tr>
<td>Supplemental Infrastructure Development</td>
<td>15.99%</td>
<td>8.27%</td>
<td>3.36</td>
<td>1.74</td>
</tr>
<tr>
<td>Transportation</td>
<td>14.42%</td>
<td>9.10%</td>
<td>3.03</td>
<td>1.91</td>
</tr>
<tr>
<td>Switching Policy</td>
<td>13.20%</td>
<td>9.07%</td>
<td>2.77</td>
<td>1.90</td>
</tr>
<tr>
<td>Legal Fees &amp; Fines</td>
<td>10.68%</td>
<td>8.56%</td>
<td>2.24</td>
<td>1.80</td>
</tr>
<tr>
<td>Licensing</td>
<td>8.91%</td>
<td>8.88%</td>
<td>1.87</td>
<td>1.86</td>
</tr>
</tbody>
</table>
Fig. 16. Weights of Costs Objectives through Simple Ranking Technique Including One Standard Deviation Above and Below the Mean
To investigate the significance of the difference in the means, not the weights, for each costs objective, a Wilcoxon Signed Ranks Test was run comparing each costs objective to every other costs objective with the statistical software SPSS. The results are listed in Table 27. The table is set up such that costs objective 1 has a larger mean than costs objective 2 and their means including their variances are being compared to each other. For these results, a large number of the comparisons demonstrate no significant difference between the means at the 95% confidence level. The cases that demonstrate no statistically significant difference at the 95% confidence level are when comparing Facility Construction, Operation, and Maintenance to Proliferation Prevention or Supplemental Infrastructure Development, when comparing Proliferation Prevention to Supplemental Infrastructure Development, when comparing Supplemental Infrastructure Development to Transportation or Switching Policy, when comparing Transportation to Switching Policy, when comparing Switching Policy to Legal Fees and Fines, and when comparing Legal Fees and Fines to Licensing.
Table 27. Statistical Comparison of Means of Costs Objectives using Simple Ranking for Significant Differences with Wilcoxon Signed Ranks Test

<table>
<thead>
<tr>
<th>Costs Objective 1</th>
<th>Costs Objective 2</th>
<th>Z Score</th>
<th>Sig. (p=)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facility Con., Oper., &amp; Maint.</td>
<td>Proliferation Prevention</td>
<td>-0.089</td>
<td>0.929</td>
</tr>
<tr>
<td>Facility Con., Oper., &amp; Maint.</td>
<td>Supplemental Infra. Dev.</td>
<td>1.632</td>
<td>0.103</td>
</tr>
<tr>
<td>Facility Con., Oper., &amp; Maint.</td>
<td>Transportation</td>
<td>2.464</td>
<td>0.014</td>
</tr>
<tr>
<td>Facility Con., Oper., &amp; Maint.</td>
<td>Switching Policy</td>
<td>2.844</td>
<td>0.004</td>
</tr>
<tr>
<td>Facility Con., Oper., &amp; Maint.</td>
<td>Legal Fees and Fines</td>
<td>4.100</td>
<td>0.000</td>
</tr>
<tr>
<td>Facility Con., Oper., &amp; Maint.</td>
<td>Licensing</td>
<td>4.521</td>
<td>0.000</td>
</tr>
<tr>
<td>Proliferation Prevention</td>
<td>Supplemental Infra. Dev.</td>
<td>1.480</td>
<td>0.139</td>
</tr>
<tr>
<td>Proliferation Prevention</td>
<td>Transportation</td>
<td>2.231</td>
<td>0.026</td>
</tr>
<tr>
<td>Proliferation Prevention</td>
<td>Switching Policy</td>
<td>2.906</td>
<td>0.004</td>
</tr>
<tr>
<td>Proliferation Prevention</td>
<td>Legal Fees and Fines</td>
<td>3.908</td>
<td>0.000</td>
</tr>
<tr>
<td>Proliferation Prevention</td>
<td>Licensing</td>
<td>4.622</td>
<td>0.000</td>
</tr>
<tr>
<td>Supplemental Infra. Dev.</td>
<td>Transportation</td>
<td>1.148</td>
<td>0.251</td>
</tr>
<tr>
<td>Supplemental Infra. Dev.</td>
<td>Switching Policy</td>
<td>1.709</td>
<td>0.087</td>
</tr>
<tr>
<td>Supplemental Infra. Dev.</td>
<td>Legal Fees and Fines</td>
<td>3.234</td>
<td>0.001</td>
</tr>
<tr>
<td>Supplemental Infra. Dev.</td>
<td>Licensing</td>
<td>4.182</td>
<td>0.000</td>
</tr>
<tr>
<td>Transportation</td>
<td>Switching Policy</td>
<td>0.885</td>
<td>0.376</td>
</tr>
<tr>
<td>Transportation</td>
<td>Legal Fees and Fines</td>
<td>2.148</td>
<td>0.032</td>
</tr>
<tr>
<td>Transportation</td>
<td>Licensing</td>
<td>2.915</td>
<td>0.004</td>
</tr>
<tr>
<td>Switching Policy</td>
<td>Legal Fees and Fines</td>
<td>1.481</td>
<td>0.138</td>
</tr>
<tr>
<td>Switching Policy</td>
<td>Licensing</td>
<td>2.629</td>
<td>0.009</td>
</tr>
<tr>
<td>Legal Fees and Fines</td>
<td>Licensing</td>
<td>1.491</td>
<td>0.136</td>
</tr>
</tbody>
</table>
6.4.3 Simple Ranking: Opportunities

The collected sample size for the first question on the opportunities survey was 92, and the frequency table of the responses for each ranking is shown in Appendix H in Table 61.

The weights were derived from this frequency table based on the interpretation scheme detailed in §6.4. The results for the opportunities objectives can be seen numerically in Table 28 and graphically in 17. It should be noted that the mean values within the objectives hierarchy will not directly compare with the other hierarchies because of the different numerical interpretation scheme resulting from there being only six objectives. Therefore, the results should only be taken within the context of this group.

<table>
<thead>
<tr>
<th>Opportunities Objective</th>
<th>Weight</th>
<th>SD</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long-term Electricity Production</td>
<td>23.48%</td>
<td>9.50%</td>
<td>3.52</td>
<td>1.43</td>
</tr>
<tr>
<td>New Technology Development</td>
<td>19.86%</td>
<td>11.40%</td>
<td>2.98</td>
<td>1.71</td>
</tr>
<tr>
<td>American Economic Development</td>
<td>19.20%</td>
<td>9.57%</td>
<td>2.88</td>
<td>1.44</td>
</tr>
<tr>
<td>Nuclear Industry Growth</td>
<td>14.86%</td>
<td>10.04%</td>
<td>2.23</td>
<td>1.51</td>
</tr>
<tr>
<td>Energy Policy Leadership</td>
<td>13.55%</td>
<td>9.50%</td>
<td>2.03</td>
<td>1.43</td>
</tr>
<tr>
<td>U.S. Government Competence</td>
<td>9.06%</td>
<td>12.17%</td>
<td>1.36</td>
<td>1.83</td>
</tr>
</tbody>
</table>
Fig. 17. Weights of Opportunities Objectives through Simple Ranking Technique Including One Standard Deviation Above and Below the Mean
To investigate the significance of the difference in the means, not the weights, for each opportunities objective, a Wilcoxon Signed Ranks Test was run comparing each opportunities objective to every other opportunities objective with the statistical software SPSS. The results are listed in Table 29. The table is set up such that opportunities objective 1 has a larger mean than opportunities objective 2 and their means including their variances are being compared to each other. For these results, the majority of comparisons demonstrated a statistically significant difference at the 95% confidence level. The only opportunities objectives that were not statistically significantly different at the 95% confidence level were when comparing New Technology Development to American Economic Development, and when comparing Nuclear Industry Growth to Energy Policy Leadership.
Table 29. Statistical Comparison of Means of Opportunities Objectives using Simple Ranking for Significant Differences with Wilcoxon Signed Ranks Test

<table>
<thead>
<tr>
<th>Opportunities Objective 1</th>
<th>Opportunities Objective 2</th>
<th>Z Score</th>
<th>Sig. (p=)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long-term Elec. Production</td>
<td>New Technology Development</td>
<td>2.043</td>
<td>0.041</td>
</tr>
<tr>
<td>Long-term Elec. Production</td>
<td>American Economic Dev.</td>
<td>2.933</td>
<td>0.003</td>
</tr>
<tr>
<td>Long-term Elec. Production</td>
<td>Nuclear Industry Growth</td>
<td>5.013</td>
<td>0.000</td>
</tr>
<tr>
<td>Long-term Elec. Production</td>
<td>Energy Policy Leadership</td>
<td>5.327</td>
<td>0.000</td>
</tr>
<tr>
<td>Long-term Elec. Production</td>
<td>U.S. Gov. Competence</td>
<td>6.144</td>
<td>0.000</td>
</tr>
<tr>
<td>New Technology Development</td>
<td>American Economic Dev.</td>
<td>0.345</td>
<td>0.730</td>
</tr>
<tr>
<td>New Technology Development</td>
<td>Nuclear Industry Growth</td>
<td>2.860</td>
<td>0.004</td>
</tr>
<tr>
<td>New Technology Development</td>
<td>Energy Policy Leadership</td>
<td>3.846</td>
<td>0.000</td>
</tr>
<tr>
<td>New Technology Development</td>
<td>U.S. Gov. Competence</td>
<td>4.427</td>
<td>0.000</td>
</tr>
<tr>
<td>American Economic Dev.</td>
<td>Nuclear Industry Growth</td>
<td>2.744</td>
<td>0.006</td>
</tr>
<tr>
<td>American Economic Dev.</td>
<td>U.S. Gov. Competence</td>
<td>4.825</td>
<td>0.000</td>
</tr>
<tr>
<td>Nuclear Industry Growth</td>
<td>Energy Policy Leadership</td>
<td>0.795</td>
<td>0.427</td>
</tr>
<tr>
<td>Nuclear Industry Growth</td>
<td>U.S. Gov. Competence</td>
<td>3.118</td>
<td>0.002</td>
</tr>
<tr>
<td>Energy Policy Leadership</td>
<td>U.S. Gov. Competence</td>
<td>2.901</td>
<td>0.004</td>
</tr>
</tbody>
</table>
6.4.4 Simple Ranking: Risks

The collected sample size for the first question on the costs survey was 84, and the frequency table of the responses for each ranking is shown in Appendix H in Table 62.

The weights were derived from this frequency table based on the interpretation scheme detailed in §6.4. The results for the costs objectives can be seen numerically in Table 30 and graphically in Figure 18.

<table>
<thead>
<tr>
<th>Risks Objective</th>
<th>Weight</th>
<th>Weight SD</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accidents or Nuclear Material Release</td>
<td>20.92%</td>
<td>6.32%</td>
<td>4.39</td>
<td>1.33</td>
</tr>
<tr>
<td>Radiation Exposure</td>
<td>20.80%</td>
<td>8.16%</td>
<td>4.37</td>
<td>1.71</td>
</tr>
<tr>
<td>Potential Future Burden</td>
<td>17.46%</td>
<td>7.76%</td>
<td>3.67</td>
<td>1.63</td>
</tr>
<tr>
<td>Proliferation Potential</td>
<td>12.98%</td>
<td>8.66%</td>
<td>2.73</td>
<td>1.82</td>
</tr>
<tr>
<td>Supply Availability</td>
<td>11.62%</td>
<td>8.57%</td>
<td>2.44</td>
<td>1.80</td>
</tr>
<tr>
<td>Public or Political Rejection</td>
<td>9.86%</td>
<td>8.65%</td>
<td>2.07</td>
<td>1.82</td>
</tr>
<tr>
<td>Technical Feasibility</td>
<td>6.35%</td>
<td>7.90%</td>
<td>1.33</td>
<td>1.66</td>
</tr>
</tbody>
</table>
Fig. 18. Weights of Risks Objectives through Simple Ranking Technique Including One Standard Deviation Above and Below the Mean
To investigate the significance of the difference in the means, not the weights, for each risks objective, a Wilcoxon Signed Ranks Test was run comparing each risks objective to every other risks objective with the statistical software SPSS. The results are listed in Table 31. The table is set up such that risks objective 1 has a larger mean than risks objective 2 and their means including their variances are being compared to each other. For these results, the majority of the comparisons demonstrate a significant difference between the means at the 95% confidence level. The cases that demonstrate no statistically significant difference at the 95% confidence level are when comparing Accidents or Nuclear Material Release to Radiation Exposure, or Proliferation Potential to Supply Availability, or Supply Availability to Public or Political Rejection.
<table>
<thead>
<tr>
<th>Risks Objective 1</th>
<th>Risks Objective 2</th>
<th>Z Score</th>
<th>Sig. ($p=$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accidents or Nuc. Mat. Release</td>
<td>Radiation Exposure</td>
<td>0.160</td>
<td>0.873</td>
</tr>
<tr>
<td>Accidents or Nuc. Mat. Release</td>
<td>Potential Future Burden</td>
<td>2.757</td>
<td>0.006</td>
</tr>
<tr>
<td>Accidents or Nuc. Mat. Release</td>
<td>Proliferation Potential</td>
<td>5.378</td>
<td>0.000</td>
</tr>
<tr>
<td>Accidents or Nuc. Mat. Release</td>
<td>Supply Availability</td>
<td>5.655</td>
<td>0.000</td>
</tr>
<tr>
<td>Accidents or Nuc. Mat. Release</td>
<td>Public or Political Rejection</td>
<td>6.114</td>
<td>0.000</td>
</tr>
<tr>
<td>Accidents or Nuc. Mat. Release</td>
<td>Technical Feasibility</td>
<td>7.339</td>
<td>0.000</td>
</tr>
<tr>
<td>Radiation Exposure</td>
<td>Potential Future Burden</td>
<td>2.460</td>
<td>0.014</td>
</tr>
<tr>
<td>Radiation Exposure</td>
<td>Proliferation Potential</td>
<td>4.796</td>
<td>0.000</td>
</tr>
<tr>
<td>Radiation Exposure</td>
<td>Supply Availability</td>
<td>4.905</td>
<td>0.000</td>
</tr>
<tr>
<td>Radiation Exposure</td>
<td>Public or Political Rejection</td>
<td>5.757</td>
<td>0.000</td>
</tr>
<tr>
<td>Radiation Exposure</td>
<td>Technical Feasibility</td>
<td>6.967</td>
<td>0.000</td>
</tr>
<tr>
<td>Potential Future Burden</td>
<td>Proliferation Potential</td>
<td>2.874</td>
<td>0.004</td>
</tr>
<tr>
<td>Potential Future Burden</td>
<td>Supply Availability</td>
<td>4.061</td>
<td>0.000</td>
</tr>
<tr>
<td>Potential Future Burden</td>
<td>Public or Political Rejection</td>
<td>4.522</td>
<td>0.000</td>
</tr>
<tr>
<td>Potential Future Burden</td>
<td>Technical Feasibility</td>
<td>6.723</td>
<td>0.000</td>
</tr>
<tr>
<td>Proliferation Potential</td>
<td>Supply Availability</td>
<td>0.938</td>
<td>0.348</td>
</tr>
<tr>
<td>Proliferation Potential</td>
<td>Public or Political Rejection</td>
<td>2.315</td>
<td>0.021</td>
</tr>
<tr>
<td>Proliferation Potential</td>
<td>Technical Feasibility</td>
<td>4.039</td>
<td>0.000</td>
</tr>
<tr>
<td>Supply Availability</td>
<td>Public or Political Rejection</td>
<td>1.610</td>
<td>0.107</td>
</tr>
<tr>
<td>Supply Availability</td>
<td>Technical Feasibility</td>
<td>3.341</td>
<td>0.001</td>
</tr>
<tr>
<td>Public or Political Rejection</td>
<td>Technical Feasibility</td>
<td>2.210</td>
<td>0.027</td>
</tr>
</tbody>
</table>
6.5 Results for Objectives Through AHP

In addition to the previous method of developing weights, AHP was once again used. As in the case of the subject matter experts, not all respondents who completed the simple ranking of benefits and opportunities objectives would complete the entirety of the pairwise comparisons. Thus the sample sizes were reduced for the benefits objectives from 93 to 87, and for the opportunities objectives from 92 to 86. The costs objectives and the risks objectives sample sizes remained constant as the respondents of these two surveys did complete all of the pairwise comparisons. With the same numerical interpretation scheme as before, see §5.3.2 Table 10, three separate analyses were done on each objective hierarchy, one for each scale: integer, balanced, and power.

The same code to evaluate the subject matter expert data was altered to evaluate all of the responses for each hierarchy survey under each numerical interpretation scheme, and to subsequently derive the weights for each objective from each respondent as well as each respondent’s consistency index, i.e., the level of inconsistency in their responses. After each respondent’s weights were derived, the arithmetic mean and the normalized geometric mean were used to get weight values. Additionally, to find the spread of the data the arithmetic standard deviation was used and the geometric standard deviation was used. Once again see Appendix D for a full discussion on both the geometric and arithmetic means and standard deviations.

As before, when using the arithmetic mean of each respondents weights for the different objectives hierarchies, the sum of the arithmetic means would equal 100% and no further scaling was required. When using the geometric mean of each respondents weights for the different objectives hierarchies, the sum of the geometric means would not equal 100% and so the geometric mean of each objective was normalized.
over the sum of the geometric means of all objectives in that objective’s hierarchy.

Additionally, the effect of inconsistency on each hierarchy was evaluated by performing the analysis at four different consistency index thresholds. The first, or no threshold, included the weights from all participants regardless of their consistency index. The second was a 20% consistency index threshold, i.e., respondents with consistency indexes greater than 20% were removed from the analysis. Likewise, the third and forth thresholds were for greater than 15% and 10% consistency indexes respectively.

The different weights and sample sizes for each numerical interpretation scheme and for no consistency index threshold and for 10% consistency index threshold have been tabulated in Appendices I through K. Presented in the following tables are the values of the arithmetic mean, denoted ‘A. Weight’, and its standard deviation, denoted ‘A. Weight SD’, along with the geometric mean, denoted ‘G. Weight’ and the geometric standard deviation, denoted ‘G. Weight SD’ under the integer numerical interpretation at the 10% consistency index threshold. Note that while the arithmetic distribution can be described by adding or subtracting the arithmetic standard deviation to or from the arithmetic mean, the geometric distribution is described by multiplying or dividing the geometric mean by the geometric standard deviation.
6.5.1 Rates of Reduction for AHP Weights

The results of the sample size versus the inconsistency threshold can be seen in Table 32. For comparison, the percentage reduction in the subject matter expert evaluation was 46%, see §5.3.2.1. Additionally, for the figures and tables in the subsequent four sections, the sample sizes of each result are from the 10% inconsistency threshold column, i.e., Benefits has a sample size of 34, Costs has a sample size of 25, Opportunities has a sample size of 38, and Risks has a sample size of 33.

Table 32. Effect of Inconsistency Threshold on Sample Sizes of Surveys Collected from the General Public for Objectives Hierarchies with Integer Scale

<table>
<thead>
<tr>
<th>Hierarchy</th>
<th>No Threshold</th>
<th>20% Inconsistency</th>
<th>15% Inconsistency</th>
<th>10% Inconsistency</th>
<th>Percent Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benefits</td>
<td>87</td>
<td>55</td>
<td>45</td>
<td>34</td>
<td>61%</td>
</tr>
<tr>
<td>Costs</td>
<td>70</td>
<td>44</td>
<td>37</td>
<td>25</td>
<td>64%</td>
</tr>
<tr>
<td>Opportunities</td>
<td>86</td>
<td>60</td>
<td>47</td>
<td>38</td>
<td>56%</td>
</tr>
<tr>
<td>Risks</td>
<td>84</td>
<td>55</td>
<td>42</td>
<td>33</td>
<td>61%</td>
</tr>
<tr>
<td>Total</td>
<td>327</td>
<td>214</td>
<td>171</td>
<td>130</td>
<td>60%</td>
</tr>
</tbody>
</table>
### 6.5.2 AHP Weights: Benefits

Table 33. Weights Table of Benefits Objectives for AHP using Integer Scale at 10% Consistency Index Threshold

<table>
<thead>
<tr>
<th>Benefits Objective</th>
<th>A. Weight</th>
<th>G. Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A. Weight</td>
<td>G. Weight</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>SD</td>
</tr>
<tr>
<td>Fuel Requirement Reduction</td>
<td>21.10%</td>
<td>22.61%</td>
</tr>
<tr>
<td></td>
<td>8.29%</td>
<td>1.54</td>
</tr>
<tr>
<td>Disposal Flexibility</td>
<td>16.68%</td>
<td>17.47%</td>
</tr>
<tr>
<td></td>
<td>7.58%</td>
<td>1.62</td>
</tr>
<tr>
<td>Local Economic Development</td>
<td>15.45%</td>
<td>14.62%</td>
</tr>
<tr>
<td></td>
<td>9.69%</td>
<td>1.98</td>
</tr>
<tr>
<td>National Infrastructure Development</td>
<td>13.99%</td>
<td>14.67%</td>
</tr>
<tr>
<td></td>
<td>6.47%</td>
<td>1.60</td>
</tr>
<tr>
<td>Increase Technical Workforce</td>
<td>11.89%</td>
<td>11.85%</td>
</tr>
<tr>
<td></td>
<td>6.18%</td>
<td>1.82</td>
</tr>
<tr>
<td>Public &amp; Political Acceptance</td>
<td>11.00%</td>
<td>9.63%</td>
</tr>
<tr>
<td></td>
<td>8.36%</td>
<td>2.18</td>
</tr>
<tr>
<td>Legal Resolution</td>
<td>9.89%</td>
<td>9.16%</td>
</tr>
<tr>
<td></td>
<td>6.47%</td>
<td>2.04</td>
</tr>
</tbody>
</table>
Fig. 19. Arithmetic and Geometric Weights of Benefits Objectives Including 1 Standard Deviation Above and Below Mean using Integer Scale at 10% Consistency Index Threshold
To investigate the significance of the difference in the weights, not the means, for each benefits objective, a Wilcoxon Signed Ranks Test was run comparing each benefits objective to every other benefits objective with the statistical software SPSS. The results are listed in Table 34. The table is set up such that benefits objective 1 has a larger mean than benefits objective 2 and their means including their variances are being compared to each other. For these results, a large number of the comparisons demonstrate no significant difference between the means at the 95% confidence level. The cases that do not demonstrate a statistically significant difference at the 95% confidence level are when comparing Disposal Flexibility to Local Economic Development or National Infrastructure Development, when comparing Local Economic Development to National Infrastructure Development or Public and Political Acceptance, when comparing National Infrastructure Development to Increase Technical Workforce or Public and Political Acceptance, when comparing Increase Technical Workforce to Public and Political Acceptance or Legal Resolution, or when comparing Public and Political Acceptance to Legal Resolution.
Table 34. Statistical Comparison of Weights of Benefits Objectives using AHP for Significant Differences with Wilcoxon Signed Ranks Test

<table>
<thead>
<tr>
<th>Benefits Objective 1</th>
<th>Benefits Objective 2</th>
<th>Z Score</th>
<th>Sig. (p=)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Requirement Reduction</td>
<td>Disposal Flexibility</td>
<td>2.866</td>
<td>0.004</td>
</tr>
<tr>
<td>Fuel Requirement Reduction</td>
<td>Local Economic Development</td>
<td>2.163</td>
<td>0.031</td>
</tr>
<tr>
<td>Fuel Requirement Reduction</td>
<td>National Infrastructure Dev.</td>
<td>3.195</td>
<td>0.001</td>
</tr>
<tr>
<td>Fuel Requirement Reduction</td>
<td>Increase Technical Workforce</td>
<td>3.619</td>
<td>0.000</td>
</tr>
<tr>
<td>Fuel Requirement Reduction</td>
<td>Public and Political Acceptance</td>
<td>3.748</td>
<td>0.000</td>
</tr>
<tr>
<td>Fuel Requirement Reduction</td>
<td>Legal Resolution</td>
<td>3.892</td>
<td>0.000</td>
</tr>
<tr>
<td>Disposal Flexibility</td>
<td>Local Economic Development</td>
<td>0.638</td>
<td>0.524</td>
</tr>
<tr>
<td>Disposal Flexibility</td>
<td>National Infrastructure Dev.</td>
<td>1.393</td>
<td>0.163</td>
</tr>
<tr>
<td>Disposal Flexibility</td>
<td>Increase Technical Workforce</td>
<td>2.210</td>
<td>0.027</td>
</tr>
<tr>
<td>Disposal Flexibility</td>
<td>Public and Political Acceptance</td>
<td>2.502</td>
<td>0.012</td>
</tr>
<tr>
<td>Disposal Flexibility</td>
<td>Legal Resolution</td>
<td>3.238</td>
<td>0.001</td>
</tr>
<tr>
<td>Local Economic Development</td>
<td>National Infrastructure Dev.</td>
<td>0.292</td>
<td>0.770</td>
</tr>
<tr>
<td>Local Economic Development</td>
<td>Increase Technical Workforce</td>
<td>2.090</td>
<td>0.037</td>
</tr>
<tr>
<td>Local Economic Development</td>
<td>Public and Political Acceptance</td>
<td>1.658</td>
<td>0.097</td>
</tr>
<tr>
<td>Local Economic Development</td>
<td>Legal Resolution</td>
<td>2.090</td>
<td>0.037</td>
</tr>
<tr>
<td>National Infrastructure Dev.</td>
<td>Increase Technical Workforce</td>
<td>1.384</td>
<td>0.166</td>
</tr>
<tr>
<td>National Infrastructure Dev.</td>
<td>Public and Political Acceptance</td>
<td>1.441</td>
<td>0.149</td>
</tr>
<tr>
<td>National Infrastructure Dev.</td>
<td>Legal Resolution</td>
<td>2.451</td>
<td>0.014</td>
</tr>
<tr>
<td>Increase Technical Workforce</td>
<td>Public and Political Acceptance</td>
<td>0.913</td>
<td>0.361</td>
</tr>
<tr>
<td>Increase Technical Workforce</td>
<td>Legal Resolution</td>
<td>1.333</td>
<td>0.182</td>
</tr>
<tr>
<td>Public and Political Acceptance</td>
<td>Legal Resolution</td>
<td>0.390</td>
<td>0.696</td>
</tr>
</tbody>
</table>
### 6.5.3 AHP Weights: Costs

Table 35. Weights Table of Costs Objectives for AHP using Integer Scale at 10% Consistency Index Threshold

<table>
<thead>
<tr>
<th>Costs Objective</th>
<th>A. Weight</th>
<th>A. Weight</th>
<th>G. Weight</th>
<th>G. Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SD</td>
<td>SD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proliferation Prevention</td>
<td>19.68%</td>
<td>12.79%</td>
<td>18.81%</td>
<td>1.75</td>
</tr>
<tr>
<td>Facility Construction, Operation, &amp; Maintenance</td>
<td>19.64%</td>
<td>8.38%</td>
<td>20.54%</td>
<td>1.45</td>
</tr>
<tr>
<td>Supplemental Infrastructure Development</td>
<td>14.69%</td>
<td>7.54%</td>
<td>15.00%</td>
<td>1.55</td>
</tr>
<tr>
<td>Transportation</td>
<td>13.65%</td>
<td>3.94%</td>
<td>14.67%</td>
<td>1.39</td>
</tr>
<tr>
<td>Switching Policy</td>
<td>13.38%</td>
<td>5.43%</td>
<td>13.77%</td>
<td>1.59</td>
</tr>
<tr>
<td>Licensing</td>
<td>9.65%</td>
<td>5.65%</td>
<td>8.77%</td>
<td>2.03</td>
</tr>
<tr>
<td>Legal Fees &amp; Fines</td>
<td>9.32%</td>
<td>5.65%</td>
<td>8.43%</td>
<td>2.03</td>
</tr>
</tbody>
</table>
Fig. 20. Arithmetic and Geometric Weights of Costs Objectives Including 1 Standard Deviation Above and Below Mean using Integer Scale at 10% Consistency Index Threshold
To investigate the significance of the difference in the weights, not the means, for each costs objective, a Wilcoxon Signed Ranks Test was run comparing each costs objective to every other costs objective with the statistical software SPSS. The results are listed in Table 36. The table is set up such that costs objective 1 has a larger mean than costs objective 2 and their means including their variances are being compared to each other. For these results, a large number of the comparisons demonstrate no significant difference between the means at the 95% confidence level. The cases that demonstrate no statistically significant difference at the 95% confidence level are when comparing Proliferation Prevention to Facility Construction, Operation, and Maintenance, Supplemental Infrastructure Development, Transportation, or Switching Policy, when comparing Supplemental Infrastructure Development to Transportation or Switching Policy, when comparing Transportation to Switching Policy, or when comparing Licensing to Legal Fees and Fines.
Table 36. Statistical Comparison of Weights of Costs Objectives using AHP for Significant Differences with Wilcoxon Signed Ranks Test

<table>
<thead>
<tr>
<th>Costs Objective 1</th>
<th>Costs Objective 2</th>
<th>Z Score</th>
<th>Sig. (p=)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proliferation Prevention</td>
<td>Facility Con., Oper., &amp; Maint.</td>
<td>-0.544</td>
<td>0.586</td>
</tr>
<tr>
<td>Proliferation Prevention</td>
<td>Supplemental Infra. Dev.</td>
<td>1.396</td>
<td>0.163</td>
</tr>
<tr>
<td>Proliferation Prevention</td>
<td>Transportation</td>
<td>1.706</td>
<td>0.088</td>
</tr>
<tr>
<td>Proliferation Prevention</td>
<td>Switching Policy</td>
<td>1.764</td>
<td>0.078</td>
</tr>
<tr>
<td>Proliferation Prevention</td>
<td>Licensing</td>
<td>2.591</td>
<td>0.010</td>
</tr>
<tr>
<td>Proliferation Prevention</td>
<td>Legal Fees and Fines</td>
<td>3.070</td>
<td>0.002</td>
</tr>
<tr>
<td>Facility Con., Oper., &amp; Maint.</td>
<td>Supplemental Infra. Dev.</td>
<td>2.675</td>
<td>0.007</td>
</tr>
<tr>
<td>Facility Con., Oper., &amp; Maint.</td>
<td>Transportation</td>
<td>2.722</td>
<td>0.006</td>
</tr>
<tr>
<td>Facility Con., Oper., &amp; Maint.</td>
<td>Switching Policy</td>
<td>2.627</td>
<td>0.009</td>
</tr>
<tr>
<td>Facility Con., Oper., &amp; Maint.</td>
<td>Licensing</td>
<td>3.549</td>
<td>0.000</td>
</tr>
<tr>
<td>Facility Con., Oper., &amp; Maint.</td>
<td>Legal Fees and Fines</td>
<td>3.309</td>
<td>0.001</td>
</tr>
<tr>
<td>Supplemental Infra. Dev.</td>
<td>Transportation</td>
<td>0.341</td>
<td>0.733</td>
</tr>
<tr>
<td>Supplemental Infra. Dev.</td>
<td>Switching Policy</td>
<td>0.402</td>
<td>0.687</td>
</tr>
<tr>
<td>Supplemental Infra. Dev.</td>
<td>Licensing</td>
<td>2.548</td>
<td>0.011</td>
</tr>
<tr>
<td>Supplemental Infra. Dev.</td>
<td>Legal Fees and Fines</td>
<td>2.817</td>
<td>0.005</td>
</tr>
<tr>
<td>Transportation</td>
<td>Switching Policy</td>
<td>0.827</td>
<td>0.408</td>
</tr>
<tr>
<td>Transportation</td>
<td>Licensing</td>
<td>2.548</td>
<td>0.011</td>
</tr>
<tr>
<td>Transportation</td>
<td>Legal Fees and Fines</td>
<td>2.330</td>
<td>0.020</td>
</tr>
<tr>
<td>Switching Policy</td>
<td>Licensing</td>
<td>2.548</td>
<td>0.011</td>
</tr>
<tr>
<td>Switching Policy</td>
<td>Legal Fees and Fines</td>
<td>2.817</td>
<td>0.005</td>
</tr>
<tr>
<td>Licensing</td>
<td>Legal Fees and Fines</td>
<td>0.166</td>
<td>0.868</td>
</tr>
</tbody>
</table>
### 6.5.4 AHP Weights: Opportunities

Table 37. Weights Table of Opportunities Objectives for AHP using Integer Scale at 10% Consistency Index Threshold

<table>
<thead>
<tr>
<th>Opportunities Objective</th>
<th>A. Weight</th>
<th>A. Weight SD</th>
<th>G. Weight</th>
<th>G. Weight SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long-term Electricity Production</td>
<td>24.73%</td>
<td>12.11%</td>
<td>25.27%</td>
<td>1.66</td>
</tr>
<tr>
<td>American Economic Development</td>
<td>20.44%</td>
<td>9.39%</td>
<td>20.77%</td>
<td>1.76</td>
</tr>
<tr>
<td>New Technology Development</td>
<td>20.39%</td>
<td>9.59%</td>
<td>20.97%</td>
<td>1.65</td>
</tr>
<tr>
<td>U.S. Government Competence</td>
<td>11.89%</td>
<td>6.89%</td>
<td>11.26%</td>
<td>1.95</td>
</tr>
<tr>
<td>Energy Policy Leadership</td>
<td>11.39%</td>
<td>7.00%</td>
<td>10.73%</td>
<td>1.94</td>
</tr>
<tr>
<td>Nuclear Industry Growth</td>
<td>11.17%</td>
<td>5.80%</td>
<td>11.00%</td>
<td>1.81</td>
</tr>
</tbody>
</table>
Fig. 21. Arithmetic and Geometric Weights of Opportunities Objectives Including 1 Standard Deviation Above and Below Mean using Integer Scale at 10% Consistency Index Threshold
To investigate the significance of the difference in the weights, not the means, for each opportunities objective, a Wilcoxon Signed Ranks Test was run comparing each opportunities objective to every other opportunities objective with the statistical software SPSS. The results are listed in Table 38. The table is set up such that opportunities objective 1 has a larger mean than opportunities objective 2 and their means including their variances are being compared to each other. For these results, the majority of comparisons demonstrated a statistically significant difference at the 95% confidence level. The only opportunities objectives that were not statistically significantly different at the 95% confidence level were when comparing Long-term Electricity Production to American Economic Development or New Technology Development, when comparing American Economic Development to New Technology Development, when comparing U.S. Government Competence to Energy Policy Leadership or Nuclear Industry Growth, or when comparing Energy Policy Leadership to Nuclear Industry Growth.
Table 38. Statistical Comparison of Means of Opportunities Objectives using AHP for Significant Differences with Wilcoxon Signed Ranks Test

<table>
<thead>
<tr>
<th>Opportunities Objective 1</th>
<th>Opportunities Objective 2</th>
<th>Z Score</th>
<th>Sig. (p=)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long-term Elec. Production</td>
<td>American Economic Dev.</td>
<td>1.344</td>
<td>0.179</td>
</tr>
<tr>
<td>Long-term Elec. Production</td>
<td>New Technology Development</td>
<td>1.344</td>
<td>0.179</td>
</tr>
<tr>
<td>Long-term Elec. Production</td>
<td>U.S. Gov. Competence</td>
<td>3.689</td>
<td>0.000</td>
</tr>
<tr>
<td>Long-term Elec. Production</td>
<td>Energy Policy Leadership</td>
<td>3.735</td>
<td>0.000</td>
</tr>
<tr>
<td>Long-term Elec. Production</td>
<td>Nuclear Industry Growth</td>
<td>1.395</td>
<td>0.000</td>
</tr>
<tr>
<td>American Economic Dev.</td>
<td>New Technology Development</td>
<td>0.023</td>
<td>0.982</td>
</tr>
<tr>
<td>American Economic Dev.</td>
<td>U.S. Gov. Competence</td>
<td>3.291</td>
<td>0.001</td>
</tr>
<tr>
<td>American Economic Dev.</td>
<td>Energy Policy Leadership</td>
<td>3.365</td>
<td>0.001</td>
</tr>
<tr>
<td>American Economic Dev.</td>
<td>Nuclear Industry Growth</td>
<td>3.988</td>
<td>0.000</td>
</tr>
<tr>
<td>New Technology Development</td>
<td>U.S. Gov. Competence</td>
<td>3.575</td>
<td>0.000</td>
</tr>
<tr>
<td>New Technology Development</td>
<td>Energy Policy Leadership</td>
<td>3.985</td>
<td>0.000</td>
</tr>
<tr>
<td>New Technology Development</td>
<td>Nuclear Industry Growth</td>
<td>4.031</td>
<td>0.000</td>
</tr>
<tr>
<td>U.S. Gov. Competence</td>
<td>Energy Policy Leadership</td>
<td>0.288</td>
<td>0.733</td>
</tr>
<tr>
<td>U.S. Gov. Competence</td>
<td>Nuclear Industry Growth</td>
<td>0.432</td>
<td>0.665</td>
</tr>
<tr>
<td>Energy Policy Leadership</td>
<td>Nuclear Industry Growth</td>
<td>-0.456</td>
<td>0.648</td>
</tr>
</tbody>
</table>
### 6.5.5 AHP Weights: Risks

Table 39. Weights Table of Risks Objectives for AHP using Integer Scale at 10% Consistency Index Threshold

<table>
<thead>
<tr>
<th>Risks Objective</th>
<th>A. Weight</th>
<th>A. Weight SD</th>
<th>G. Weight</th>
<th>G. Weight SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation Exposure</td>
<td>25.62%</td>
<td>9.12%</td>
<td>27.19%</td>
<td>1.43</td>
</tr>
<tr>
<td>Accidents or Nuclear Material Release</td>
<td>25.03%</td>
<td>7.49%</td>
<td>26.89%</td>
<td>1.39</td>
</tr>
<tr>
<td>Potential Future Burden</td>
<td>15.56%</td>
<td>8.60%</td>
<td>14.89%</td>
<td>1.85</td>
</tr>
<tr>
<td>Proliferation Potential</td>
<td>12.01%</td>
<td>10.99%</td>
<td>10.12%</td>
<td>2.08</td>
</tr>
<tr>
<td>Technical Feasibility</td>
<td>8.11%</td>
<td>4.27%</td>
<td>7.95%</td>
<td>1.72</td>
</tr>
<tr>
<td>Supply Availability</td>
<td>7.41%</td>
<td>3.89%</td>
<td>7.32%</td>
<td>1.69</td>
</tr>
<tr>
<td>Public or Political Rejection</td>
<td>6.26%</td>
<td>4.50%</td>
<td>5.63%</td>
<td>1.93</td>
</tr>
</tbody>
</table>
Fig. 22. Arithmetic and Geometric Weights of Risks Objectives Including 1 Standard Deviation Above and Below Mean using Integer Scale at 10% Consistency Index Threshold
To investigate the significance of the difference in the weights, not the means, for each risks objective, a Wilcoxon Signed Ranks Test was run comparing each risks objective to every other risks objective with the statistical software SPSS. The results are listed in Table 40. The table is set up such that risks objective 1 has a larger mean than risks objective 2 and their means including their variances are being compared to each other. For these results, the majority of the comparisons demonstrate a significant difference between the means at the 95% confidence level. The cases that demonstrate no statistically significant difference at the 95% confidence level are when comparing Radiation Exposure to Accidents or Nuclear Material Release, when comparing Potential Future Burden to Proliferation Potential, when comparing Proliferation Potential to Technical Feasibility, or when comparing Technical Feasibility to Supply Availability.
Table 40. Statistical Comparison of Weights of Risks Objectives using AHP for Significant Differences with Wilcoxon Signed Ranks Test

<table>
<thead>
<tr>
<th>Risks Objective 1</th>
<th>Risks Objective 2</th>
<th>Z Score</th>
<th>Sig. (p=)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation Exposure</td>
<td>Accidents or Nuc. Mat. Release</td>
<td>0.457</td>
<td>0.648</td>
</tr>
<tr>
<td>Radiation Exposure</td>
<td>Potential Future Burden</td>
<td>3.492</td>
<td>0.000</td>
</tr>
<tr>
<td>Radiation Exposure</td>
<td>Proliferation Potential</td>
<td>3.412</td>
<td>0.001</td>
</tr>
<tr>
<td>Radiation Exposure</td>
<td>Technical Feasibility</td>
<td>4.541</td>
<td>0.000</td>
</tr>
<tr>
<td>Radiation Exposure</td>
<td>Supply Availability</td>
<td>4.541</td>
<td>0.000</td>
</tr>
<tr>
<td>Radiation Exposure</td>
<td>Public or Political Rejection</td>
<td>4.541</td>
<td>0.000</td>
</tr>
<tr>
<td>Accidents or Nuc. Mat. Release</td>
<td>Potential Future Burden</td>
<td>3.568</td>
<td>0.000</td>
</tr>
<tr>
<td>Accidents or Nuc. Mat. Release</td>
<td>Proliferation Potential</td>
<td>3.508</td>
<td>0.000</td>
</tr>
<tr>
<td>Accidents or Nuc. Mat. Release</td>
<td>Technical Feasibility</td>
<td>4.517</td>
<td>0.000</td>
</tr>
<tr>
<td>Accidents or Nuc. Mat. Release</td>
<td>Supply Availability</td>
<td>4.541</td>
<td>0.000</td>
</tr>
<tr>
<td>Accidents or Nuc. Mat. Release</td>
<td>Public or Political Rejection</td>
<td>4.541</td>
<td>0.000</td>
</tr>
<tr>
<td>Potential Future Burden</td>
<td>Proliferation Potential</td>
<td>1.898</td>
<td>0.058</td>
</tr>
<tr>
<td>Potential Future Burden</td>
<td>Technical Feasibility</td>
<td>3.911</td>
<td>0.000</td>
</tr>
<tr>
<td>Potential Future Burden</td>
<td>Supply Availability</td>
<td>3.949</td>
<td>0.000</td>
</tr>
<tr>
<td>Potential Future Burden</td>
<td>Public or Political Rejection</td>
<td>4.180</td>
<td>0.000</td>
</tr>
<tr>
<td>Proliferation Potential</td>
<td>Technical Feasibility</td>
<td>1.057</td>
<td>0.290</td>
</tr>
<tr>
<td>Proliferation Potential</td>
<td>Supply Availability</td>
<td>1.970</td>
<td>0.049</td>
</tr>
<tr>
<td>Proliferation Potential</td>
<td>Public or Political Rejection</td>
<td>3.219</td>
<td>0.001</td>
</tr>
<tr>
<td>Technical Feasibility</td>
<td>Supply Availability</td>
<td>1.181</td>
<td>0.238</td>
</tr>
<tr>
<td>Technical Feasibility</td>
<td>Public or Political Rejection</td>
<td>3.123</td>
<td>0.002</td>
</tr>
<tr>
<td>Supply Availability</td>
<td>Public or Political Rejection</td>
<td>2.367</td>
<td>0.018</td>
</tr>
</tbody>
</table>
6.6 Discussion on Objective Weights

When compared to the original objectives in Ch. 4, the rate of reduction, i.e., 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. With the initial hierarchies and the surveys conducted at the large nuclear engineering and science conference the average reduction rate was 58% and with the revised hierarchies and the surveys conducted electronically the average reduction was 60%, see §4.3.2 Table 5 and §6.5.1 Table 32. 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 author that the new hierarchies represented 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 objectives to a point where members of the general public understand some of the relevant aspects, without diluting the meaning of the terms. Additionally, the objective weights as generated by both the simple ranking interpretation and by using AHP showed very good agreement.

Despite this agreement there were concerns about the overall validity of the surveys. The reason for these concerns was the combination of very high abandonment rates, and the very high inconsistency reduction rates. For example, with an abandonment rate of 56% and an inconsistency reduction rate of 61%, a mere 17% of individuals who started the risks survey completed it satisfactorily; or put another way, 83% of individuals who initially attempted it did not complete the risks survey.
in a satisfactory manner. The weights may give some insight into what members of
the general public find appropriate in a nuclear fuel cycle, or rather what they are
fearful of; but with the combination of high abandonment rates, high inconsistency
reduction rates, and no decisive most important objectives, it is the opinion of the
author that this general approach at gathering public insights is an ill-fated one even
if it is superior in its current iteration.

6.7 Conclusion on Objective Weights

The correct method of determining what is important in terms of a nuclear fuel
cycle, and by how much, when considering public opinion, proved more difficult than
originally thought. Armed with these results, a complete revision was undertaken to
further refine the decision making model and develop one capable of accomplishing
the herculean task of incorporating the general public’s perceptions into the selection
of a nuclear fuel cycle.
CHAPTER 7

NUCLEAR FUEL CYCLE OBJECTIVES: FINALIZED

The persistent concerns in the AHP style analysis motivated a reevaluation of the objectives hierarchy. This revision was undertaken based on the MAUT approach to MODA.

7.1 The Clarity Test

In the approach to revise the objectives of the analysis again, a much deeper literature review was conducted. In addition to the information about means, fundamental, and strategic objectives, something known as the ‘clarity test’ was discovered. The clarity test is a test that can be applied to evaluate whether the definition of an objective is defined in such a manner that an answer could possibly be given [24]. The test is such that one considers whether a clairvoyant, a person who knew the future, who had access to all information, e.g., newspapers, articles, technical documents, etc., would be able to give a value to the objective for a specific alternative [24]. If even a clairvoyant would not be able to do this, the objective is ill-defined [24]. With this knowledge in hand the objectives were completely revised so that they would pass the clarity test.

7.2 Defining the Range

As has been discussed in §2.3, defining the range of the objectives is very important in order to elicit meaningful preferences. As such each objective would also have their range defined.
7.3 Final Revision

It was understood that although much work had been done in refining the objectives, there had been fundamental flaws in the development of these objectives. Once examined under the stricter factors of the clarity test and assuring that all objectives are fundamental, drastic changes were required. The first of these was to regroup the terms under hierarchy labels different than the labels of benefits, opportunities, costs, and risks, since this type of hierarchy structuring was an artifact from AHP. Thus a fresh approach was applied. Four new groups were determined to be ‘Benefits’, ‘Physical Liabilities’, ‘Implementation Liabilities’, and ‘Costs.’

7.3.1 Costs

First under ‘Costs’, it was concluded that there is no reason why costs should be further subdivided into separate factors that would be compared against each other. The motivation for this change is simple; each factor under costs is measured using the same scale, namely dollars, and the purpose of comparing objectives against each other is so that a ratio of importance can be established between the two objectives, thus giving a weight. When comparing two objectives that are evaluated on the same scale, the values of the metrics themselves will lead to the ratio of importance. For example, if Facility Construction, Operation, and Maintenance Costs were compared to Licensing Costs, the dollar amounts of the two objectives would be sufficient to determine the ratio of importance. Additionally, reducing a dollar in any category should have an equal effect on the overall costs, a dollar toward Licensing counts the same as a dollar toward Facility Construction, Operation, and Maintenance for the total cost of the nuclear fuel cycle. Furthermore, if individual costs items were assigned different levels of importance, meaning that a dollar spent toward one ob-
jective is more important than the same dollar spent towards a different objective, there exists the possibility when comparing alternatives that the more costly alternative would be preferred even if the benefits of each alternative were exactly the same. This phenomenon is explored mathematically in the subsequent section and an example is demonstrated in Appendix C.

7.3.1.1 Preferring Higher Costs: The Problem with Weighting Individual Cost Items

Suppose a comprehensive evaluation of multiple nuclear fuel cycles has been undertaken, and only two objectives have been identified as fundamental. These objectives are *Maximize Benefits* and *Minimize Costs*. Although other fuel cycles are under evaluation, during the course of the analysis it becomes relevant to compare two nuclear fuel cycles more closely; the fuel cycles are labeled Nuclear Fuel Cycle 1 (NFC 1) and Nuclear Fuel Cycle 2 (NFC 2). In terms of *Maximize Benefits* both NFC 1 and NFC 2 are valued at the maximum of 100. However, in terms of *Minimize Costs* NFC 1 has overall more costs. Specifically, NFC 1 has total costs of $18M and NFC 2 has total costs of $17M.

Within this context, there exists no possible weighting scheme for which NFC 1 would ever be preferred to NFC 2. To show this more generally and mathematically, let us first examine the equations for deriving the final value of each alternative:

\[
V_1 = w_1 V_1(O_1) + w_2 V_1(O_2)
\]

\[
V_2 = w_1 V_2(O_1) + w_2 V_2(O_2)
\]

(7.1)

where \(V_1\) is the final value of NFC 1, \(V_2\) is the final value of NFC 2, \(w_1\) is the weight of objective 1, i.e., *Maximize Benefits*, \(w_2\) is the weight of objective 2, i.e., *Minimize Costs*, and \(V_j(O_i)\) is the value which the \(j^{th}\) alternative takes for the \(i^{th}\) objective.
If we want to understand which alternative is more preferred we can simply look at the difference between their final values such that:

\[ P = V_1 - V_2 \]  

(7.2)

\[
\begin{align*}
  P > 0 & \quad \text{NFC 1 is preferred} \\
  P = 0 & \quad \text{NFC 1 is equal to NFC 2} \\
  P < 0 & \quad \text{NFC 2 is preferred}
\end{align*}
\]

(7.3)

where \( P \) is the preference indicator used to compare alternatives.

If we insert the equations from Equation 7.1 into Equation 7.2 we arrive at the following equation:

\[ P = V_1 - V_2 \]

\[ P = (w_1 V_1(O_1) + w_2 V_1(O_2)) - (w_1 V_2(O_1) + w_2 V_2(O_2)) \]  

(7.4)

Since both NFC 1 and NFC 2 have the same value with respect to *Maximize Benefits*, i.e., 100, we can set both equal to the new term \( V(O_1) \):

\[ V_1(O_1) = V_2(O_1) = V(O_1) \]  

(7.5)

Substituting Equation 7.5 into Equation 7.4 we can simplify the preference indicator equation as:

\[ P = (w_1 V_1(O_1) + w_2 V_1(O_2)) - (w_1 V_2(O_1) + w_2 V_2(O_2)) \]

\[ P = w_1 V(O_1) + w_2 V_1(O_2) - w_1 V(O_1) - w_2 V_2(O_2) \]

\[ P = w_2 V_1(O_2) - w_2 V_2(O_2) \]

\[ P = w_2 (V_1(O_2) - V_2(O_2)) \]  

(7.6)

The result in Equation 7.6 demonstrates that the final preference between the
two alternatives is a function only of the difference in how well each alternative is valued in terms of the second objective, namely *Minimize Costs*. As the weights of objectives can only take positive values, the choice of weights will never switch the preference; rather the weights will only determine the magnitude of the preference. Thus when everything else is equal, NFC 1 will always be preferred if its total cost is less than NFC 2, i.e., $V_1(O_2)$ will be greater than $V_2(O_2)$ resulting in $P > 0$. Likewise, NFC 2 will always be preferred if its total cost is less than NFC 1, i.e., $V_2(O_2)$ will be greater than $V_1(O_2)$ resulting in $P < 0$.

However, suppose now that the same analysis was undertaken but instead of costs being combined into one item, it was thought that *Minimize Costs* should really be broken into two separate objectives such that:

\[
\begin{align*}
    w_2 &= w_{2a} + w_{2b} \\
    O_2 &= O_{2a} + O_{2b}
\end{align*}
\]  

(7.7)
(7.8)

where $w_{2a}$ represents the portion of weight that is dedicated toward the first costs objective, $w_{2b}$ represents the portion of weight that is dedicated toward the second costs objective, $O_2$ is the original costs objective’s measured value, $O_{2a}$ is first costs objectives measured value, and $O_{2b}$ is second costs objectives measured value. Thus $V_j(O_{2a})$ is the value of the $j^{th}$ alternative for the first costs objective, and $V_j(O_{2b})$ is the value of the $j^{th}$ alternative for the second costs objective. Let us suppose the first costs objective is *Minimize Facility Costs* and the second is *Minimize Non-facility Costs*. The equations for deriving the final value of each alternative are now given as follows:

\[
\begin{align*}
    V_1 &= w_1V_1(O_1) + w_{2a}V_1(O_{2a}) + w_{2b}V_1(O_{2b}) \\
    V_2 &= w_1V_2(O_1) + w_{2a}V_2(O_{2a}) + w_{2b}V_2(O_{2b})
\end{align*}
\]  

(7.9)
To determine the preference of which alternative, we can substitute Equation 7.9 into Equation 7.2; giving the following equation:

\[ P = V_1 - V_2 \]

\[ P = (w_1 V_1(O_1) + w_{2a} V_1(O_{2a}) + w_{2b} V_1(O_{2b})) - (w_1 V_2(O_1) + w_{2a} V_2(O_{2a}) + w_{2b} V_2(O_{2b})) \]  

(7.10)

Since NFC 1 and NFC 2 both have the same value in terms of benefits, we can once again substitute in Equation 7.5. This leads to the following simplified equation:

\[ P = (w_1 V_1(O_1) + w_{2a} V_1(O_{2a}) + w_{2b} V_1(O_{2b})) - (w_1 V_1(O_1) + w_{2a} V_1(O_{2a}) + w_{2b} V_1(O_{2b})) \]

\[ P = (w_2 V_1(O_{2a}) + w_{2b} V_1(O_{2b}) - w_{2a} V_2(O_{2a}) - w_{2b} V_2(O_{2b})) \]

(7.11)

The result in Equation 7.11 demonstrates that the final preference between the two alternatives is a function of both the difference in how each alternative is valued in terms of each costs objective, namely Minimize Facility Costs and Minimize Non-facility Costs, and the weight of each costs objective. Thus when everything else is equal, NFC 1 will not always be preferred even if its total costs are less than NFC 2; because the preference is determined by both the difference in value and the weights of importance. Likewise, NFC 2 will not always be preferred even if its total costs are less than NFC 1. More specifically, NFC 1 will always be preferred to NFC 2 if and only if its costs in every single costs objective are less than NFC 2. Likewise, NFC 2 will always be preferred to NFC 1 if and only if its costs in every single costs objective are less than NFC 1. To further demonstrate the truth of this argument, an example can easily be found where, using the previous preference equation, the more
costly alternative is preferred despite having the same benefits. See Appendix C for the comprehensive example.

In conclusion, if costs are weighted against each other, there arises the potential for an alternative that is overall more costly to be preferred despite having no additional benefit. Thus for the following analysis all costs items will be evaluated as one term, i.e., *Minimize Costs*.

### 7.3.1.2 Further Discussion on Costs

Already detailed in this manuscript is a thorough justification for choosing to weight total costs as a single item; however, it could be considered presumptuous to not present some opposing arguments to this costs quantification scheme. Specifically, although weighting costs differently has been shown to have the potential to produce results where a more overall costly alternative is preferred to a less costly alternative despite having the same benefits, it has been suggested that grouping costs into a single item may not take into account the importance of how money is spent. For instance, imagine a choice between spending two dollars on a cup of coffee from a coffee shop or spending twelve dollars on a coffee maker which produces the same one cup of coffee at the same quality. Although the direct benefits of having a cup of coffee might be the same, i.e., the enjoyment of the coffee and the increase productivity from the caffeine, a dollar spent towards the coffee maker is clearly an investment in the future, while a dollar spent on the cup of coffee from the coffee shop clearly has no long term benefit. However, one may argue that if a MODA was undertaken for this scenario it would be possible to incorporate the different aspects of the benefits into different objectives. Specifically, one would be able to still weight costs as a single item, but perhaps have another objective to account for the long term benefits of a coffee maker, such as Minimize Time Required to Receive Coffee.
In this manner costs can still be rated as a single item, but the other important aspects of those costs will naturally be factored into the other objectives. Truly, if one is asked “Why is a dollar spent here more important than a dollar spent there?” the answer would uncover some other important objective that would likely need to be accounted for. If individual costs were to be fundamentally important then the answer to the question “Why is a dollar spent here more important than a dollar spent there?” must be “Because it inherently is.” As there is no logical reason why a dollar spent toward one thing should be inherently more valuable than a dollar spent toward another thing, absent of benefits, there can be no reason why costs should be weighted differently.

Additionally, there exists the concept of ‘levelizing’ costs, which essentially is taking the total cost of some operation or product and dividing it by some output or value associated with that operation or product. For example, this technique can be used to measure the efficiency of energy sources by taking the cost of generating electricity divided by the amount of electricity generated so that the final values are in the units of dollar per kilowatt ($/kW). However, the author will argue that this ‘levelized’ cost is, in fact, not a cost at all, but rather it is an efficiency. Thus the author will also argue that although it is fine to compare efficiencies of various processes, this should not be done in absentia of the total costs. What really is presented in an efficiency measurement are two different but related objectives, such that one should be maximized while the other should be minimized. Thus for electricity production we would always want to minimize total costs and maximize total electricity produced, rather than simply having the plant maximize its dollars spent per kilowatt ratio. Although sometimes the only objectives considered are minimizing total costs and maximizing the efficiency; however, this is just a proxy for measuring the benefits. This can be seen more clearly in an example involving a grocery store.
When going to buy rice at a grocery store there are two things that are relevant after one has determined what type of rice to buy: the total cost and the cost per unit weight. One should not base their choice only on one aspect but rather consider both. If instead the decision was made only on the cost per unit weight, i.e., an efficiency, then the individual would have to buy the largest bag of rice in the store since this, in general, will have the best cost per unit weight. However, making a decision based only on an efficiency does not include the fact that individuals have finite resources and a limited supply of money. Thus the realistic scenario is that the individual will buy the largest bag of rice that still fits within their budget for rice, thus maximizing efficiency while still minimizing total costs to find the optimal solution. Here the efficiency is really just a proxy for the individual maximizing the benefit that they receive from their purchase. Thus costs should evaluated in absolute terms and not ‘levelized,’ since the beneficial aspects of an efficiency should already be included in other objectives.

7.3.1.3 Costs Items

It is still relevant to consider that costs can come from a multitude of factors, and to include each factor that contributes to the overall cost, but it is not relevant to compare which cost is more important. Thus the objective Minimize Costs was developed and is comprised of all the different cost items. Eighteen costs items were identified and these costs items are listed in Table 41.

Since the operating time of a nuclear fuel cycle can be on the order of decades, it begs the question, “When should costs be evaluated?” One such method that could be used is the method of discounted cash flows. This method brings all dollar values from different times to a common time, sums them, and then evaluates them at the current time. This method is logical and can be used with great success. However,
Table 41. Costs Items

<table>
<thead>
<tr>
<th>Cost Item Name</th>
<th>Cost Item Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Facilities Construction</td>
<td>C1</td>
</tr>
<tr>
<td>Primary Facilities Operation</td>
<td>C2</td>
</tr>
<tr>
<td>Primary Facilities Maintenance</td>
<td>C3</td>
</tr>
<tr>
<td>Support Facilities Construction</td>
<td>C4</td>
</tr>
<tr>
<td>Support Facilities Operation</td>
<td>C5</td>
</tr>
<tr>
<td>Support Facilities Maintenance</td>
<td>C6</td>
</tr>
<tr>
<td>Licensing Primary Facilities</td>
<td>C7</td>
</tr>
<tr>
<td>Licensing Support Facilities</td>
<td>C8</td>
</tr>
<tr>
<td>Licensing Technology</td>
<td>C9</td>
</tr>
<tr>
<td>Licensing Methodologies</td>
<td>C10</td>
</tr>
<tr>
<td>Utility Company Standard Contract Settlements</td>
<td>C11</td>
</tr>
<tr>
<td>Nuclear Theft Prevention</td>
<td>C12</td>
</tr>
<tr>
<td>New Highway Construction</td>
<td>C13</td>
</tr>
<tr>
<td>New Railway Construction</td>
<td>C14</td>
</tr>
<tr>
<td>New Work Force Development</td>
<td>C15</td>
</tr>
<tr>
<td>Transportation Vehicles</td>
<td>C16</td>
</tr>
<tr>
<td>Transportation Containers</td>
<td>C17</td>
</tr>
<tr>
<td>Transportation Operators</td>
<td>C18</td>
</tr>
</tbody>
</table>
with projects on large time scales and involving change over of leadership, e.g., the
President of the U.S. and Congress, it is the opinion of the author that a more
pragmatic approach would be to evaluate the costs at discrete time steps as separate
objectives. Specifically, the three objectives would be to minimize short-term costs,
minimize mid-term costs, and minimize long-term costs. For this analysis, short-term
costs are to be evaluated after 10 years, mid-term costs are to be evaluated after 30
years, and long-term costs are to be evaluated after 100 years. Put more plainly, years
zero through 10 are evaluated as short-term costs, years 11 through 30 are evaluated
as mid-term costs, and years 31 through 100 are evaluated as long-term costs; these
distinctions are made to avoid double-counting costs. The choice of these discrete
times is not completely arbitrary, but rather they are chosen since they may do a
“good-enough” job of describing the costs. The evaluation of each costs objective
is essentially a discounted cash flows problem but just for the length of time under
consideration.

An example of how this evaluation would be done can be seen in Figures 23 and
24. Figure 23 shows the annual costs of two separate fuel cycles, essentially the sum
of all values from Table 41, for each year after the fuel cycle is initiated. Figure 24
shows the sum, with no applied interest, of each year’s total annual cost. For this
evaluation the total cumulative cost at 10 years time would give short-term costs.
The total cumulative cost at 30 years time minus the total cumulative cost at 10
years time would give the mid-term costs. Finally, the total cumulative cost at 100
years minus the total cumulative cost at 30 years time will give the long-term costs.
The actual calculations would need to be performed in order to determine which fuel
cycle is preferred for each range in question. The finalized costs objectives and their
definitions can be seen in Table 42.
Table 42. Costs Objectives and Definitions

<table>
<thead>
<tr>
<th>Costs Objective</th>
<th>Definition</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimize Short-term Costs</td>
<td>The cumulative total cost of all items listed under “Costs Items” after 10 years of initial implementation (Billions of Dollars).</td>
<td>$50B to $10B</td>
</tr>
<tr>
<td>Minimize Mid-term Costs</td>
<td>The cumulative total cost of all items listed under “Costs Items” between 11 years after implementation and 30 years after initial implementation (Billions of Dollars).</td>
<td>$250B to $50B</td>
</tr>
<tr>
<td>Minimize Long-term Costs</td>
<td>The cumulative total cost of all items listed under “Costs Items” between 31 years after implementation and 100 years after initial implementation (Billions of Dollars).</td>
<td>$1125B to $225B</td>
</tr>
</tbody>
</table>
Fig. 23. Example of Total Annual Costs

Fig. 24. Example of Total Cumulative Costs
7.3.2 Benefits

The Benefits hierarchy was also dramatically altered. It was concluded that the majority of the benefits terms were in fact strategic objectives, and that in the context of selecting a nuclear fuel cycle, the only fundamental benefits would be to ‘maximize the reduction in nuclear fuel requirements’, and to ‘maximize the flexibility of disposal for used nuclear fuel’. The others, items such as Local Economic Development, National Infrastructure Development and an Increase in Technical Workforce, were ancillary benefits derived from a nuclear fuel cycle, that were in fact more strategic in nature. Additionally, Legal Resolution was also thought of as a strategic objective since it is not directly derived from the choice in nuclear fuel cycle. Finally, Public and Political Acceptance was transformed and included within the section Implementation Liabilities as ‘minimize the probability of unforeseen implementation problems’ since when asked “Why is this important?” the answer was “So that the fuel cycle could be more easily implemented”. Thus this section was dramatically reduced to only two objectives.

In order for the objectives to pass the clarity test, the definitions needed to be revised. The finalized benefits objectives and their definitions can be seen in Table 43. Note Maximize the Flexibility of Disposal for Used Nuclear Fuel has two separate components that will eventually be weighed against each other.

7.3.3 Physical Liabilities

The hierarchy previously known as Risks was transformed into two categories, Physical Liabilities and Implementation Liabilities. The former will be discussed in this section. Three fundamental physical liability objectives were identified, namely ‘minimize the potential of accidents or the release of nuclear material,’ ‘minimize the
<table>
<thead>
<tr>
<th>Benefits Objective</th>
<th>Definition</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximize the Reduction in Nuclear Fuel Requirements</td>
<td>The percentage reduction in the amount of nuclear fuel imported and mined after 20 years of the nuclear fuel cycle’s initial implementation.</td>
<td>0% to 100%</td>
</tr>
<tr>
<td>Maximize the Flexibility of Disposal for Used Nuclear Fuel</td>
<td>The percentage of nuclear fuel types that are acceptable 30 years after the nuclear fuel cycle’s initial implementation.</td>
<td>0% to 100%</td>
</tr>
<tr>
<td></td>
<td>The percentage of nuclear fuel sizes that are acceptable 30 years after the nuclear fuel cycle’s initial implementation.</td>
<td>0% to 100%</td>
</tr>
</tbody>
</table>
potential of nuclear material being stolen,’ and ‘minimize the radiation exposure to persons.’ The objective Public or Political Rejection like Public and Political Acceptance was transformed and included within the section Implementation Liabilities as ‘minimize the probability of unforeseen implementation problems,’ since it was also found to be a means objective. Supply Availability as well as Potential Future Burden were determined to be strategic and thus no longer included. Technical Feasibility was transformed and incorporated under Implementation Liabilities as ‘minimize the probability of unforeseen implementation problems’ and ‘minimize the time required for full implementation of the nuclear fuel cycle.’ After these changes this section consisted of three objectives.

The definitions were again revised to pass the clarity test. Minimize the Potential of Accidents or the Release of Nuclear Material and Minimize the Radiation Exposure to Persons have two separate components that will eventually be weighed against each other. The finalized physical liability objectives and their definitions can be seen in Table 44.

7.3.3.1 The International Nuclear Event Scale

The International Nuclear Event Scale (INES) is a device developed by the International Atomic Energy Agency (IAEA) to aid in communicating the significance of an event that occurs at a nuclear facility [25]. Events are classified on the scale at 7 different levels of severity, levels 1-3 are called ‘incidents,’ and levels 4-7 are called ‘accidents’ [25]. The scale is designed so that the severity of an event is about 10 times greater, an order of magnitude, for each increase in level on the scale, meaning the scale is logarithmic [25]. A representation of this scale can be seen in Figure 25.
<table>
<thead>
<tr>
<th>Physical Liabilities</th>
<th>Objective</th>
<th>Definition</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimize the Potential of Accidents</td>
<td>Minimize the Potential of Accidents or the Release of Nuclear Material</td>
<td>The probability of a serious or major accident occurring within 100 years of initial implementation of the nuclear fuel cycle. (As rated by the INES: Level 6 or 7) (see §7.3.3.1)</td>
<td>100% to 0%</td>
</tr>
<tr>
<td>Minimize the Potential of Nuclear Material</td>
<td>Minimize the Potential of Nuclear Material being Stolen</td>
<td>The probability of a successful theft of nuclear material from the nuclear fuel cycle within 100 years of operation.</td>
<td>100% to 0%</td>
</tr>
<tr>
<td>Minimize the Radiation Exposure to Persons</td>
<td>Minimize the Radiation Exposure to Persons</td>
<td>The average annual radiation exposure to workers at nuclear facilities as a percentage of the U.S. federal radiation limit.</td>
<td>100% to 0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>The average annual radiation exposure to members of the general public in counties adjacent to nuclear facilities as a percentage of the U.S. federal radiation limit.</td>
<td>100% to 0%</td>
</tr>
</tbody>
</table>
7.3.4 Implementation Liabilities

The other part of the previous Risks hierarchy was decomposed into a section known as Implementation Liabilities. The two objectives that remained in this section were ‘minimize the time required for full implementation of the nuclear fuel cycle’ and ‘minimize the probability of unforeseen implementation problems.’ These two objectives were decided upon as being fundamental to the choice of determining the optimal nuclear fuel cycle. As previously discussed in §7.3.3, many previous objectives were transformed into these two objectives. The definitions were again revised to pass the clarity test, and both objectives were comprised of one factor each. The finalized implementation liability objectives and their definitions can be seen in Table 45.

Fig. 25. International Nuclear Event Scale
Table 45. Implementation Liability Objectives and Definitions

<table>
<thead>
<tr>
<th>Implementation Liabilities Objective</th>
<th>Definition</th>
<th>Range (Worst to Best)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimize the Time Required for Full Implementation of the Nuclear Fuel Cycle</td>
<td>The length of time from present (2015) that the nuclear fuel cycle needs in order to be considered fully implemented (in years)</td>
<td>45 Years to 5 Years</td>
</tr>
<tr>
<td>Minimize the Probability of Unforeseen Implementation Problems</td>
<td>The probability that the chosen nuclear fuel cycle will experience unforeseen delays or impediments between its initial implementation and full implementation.</td>
<td>100% to 0%</td>
</tr>
</tbody>
</table>
7.3.5 Opportunities

The section previously known as *Opportunities* was determined to be entirely composed of strategic objectives and thus removed from the analysis. Although these objectives constituted aspects of nuclear fuel cycles that are worthy of consideration, when posed with the question “What else influences this?” other factors always arose. Explicitly, *American Economic Development* has a multitude of influences that are not directly attributable to the nuclear fuel cycle such as current legislation, tax rates, and the whims of the stock market. All of these factors influence the development of the American economy, and it would be inappropriate to include such an objective into the current analysis. Similarly, *Energy Policy Leadership* also has many influences outside the scope of the implementation of the nuclear fuel cycle, as does *U.S. Government Competence*, and *New Technology Growth*. *Nuclear Industry Growth* and *Energy Policy Leadership* are potential ancillary benefits that can be derived from having a resolved nuclear fuel cycle, but they are also influenced by many other factors such as the popularity of renewable energy and the price of natural gas. Although having a defined nuclear fuel cycle can influence all of these factors to some extent, they are not entirely determined by the choice in nuclear fuel cycle and thus removed from the analysis using MAUT.

7.4 Summary of New Hierarchy

The radical changes to the hierarchy spurred by the new MAUT perception changed the hierarchy to a much more compact form as seen in Figure 26. Additionally, each objective now has a definition which passes the clarity test, and has a range defined under which they will be evaluated. After these substantial improvements the new model was finally ready to be evaluated.
Fig. 26. Final Hierarchy after MAUT based Revision
CHAPTER 8

FUTURE WORK

Although the framework for evaluating the fundamental objectives based on a MAUT approach is in place, time constraints have prevented a full analysis from being included within this manuscript. This work represents the first step toward the selection of a nuclear fuel cycle for the United States that incorporates public preferences; as such there is still work that should be completed to actualize this goal. This future work will now be detailed.

8.1 A MAUT Based Evaluation

Described here is the intended methodology through which one may evaluate the alternative nuclear fuel cycles with the MAUT based model.

8.1.1 Objective Weighting and Value Functions

It was thought, by the author, that a contributing factor to the reason it appears to be so difficult for members of the general public to evaluate the different concepts on the nuclear fuel cycle is that members of the general public often times do not know what a nuclear fuel cycle even is, let alone the different objectives that need to be maximized or minimized. Understanding this, an evaluation strategy was created. The strategy is to produce a website through which individuals can learn about a generic nuclear fuel cycle in six concise steps; mining, enrichment, fabrication, electricity production, spent fuel removal or reprocessing, and final storage. After they are introduced to these basic concepts, the individuals may proceed to different webpages
where the different fundamental objectives and their sub-objectives are located along with brief descriptions about each objective. Ideally, a graphical user interface will allow the individuals to give their preferences for varying degrees of the fundamental objectives and in this way produce the required single-dimensional value functions (SDVF) for each fundamental objective. After the different SDVFs have been elicited, the respondent may encounter an additional graphical user interface where they are able to perform the swing weights analysis and develop the fundamental objective weights. Of paramount importance when eliciting opinions from the general public is to make the graphical user interfaces easy to use, understandable, and approachable. This website would be geared toward members of the general public, but it could be used with anyone from the different subject matter expert groups.

8.1.2 Alternative Value Distributions

A different website can be created to elicit the actual expected values that would be found for each alternative in terms of each fundamental objective from subject matter experts. This could be done by employing another graphical user interface which would allow the subject matter expert to first give the maximum possible value that a specific alternative nuclear fuel cycle would have for a specific fundamental objective. Afterward the respondent would give the minimum possible value that a specific alternative nuclear fuel cycle would have for a specific fundamental objective. Finally, the respondent would give the most likely value that a specific alternative nuclear fuel cycle would have for a specific fundamental objective. In this way, a triangular distribution can be created for each fundamental objective value for every alternative nuclear fuel cycle.

Although one may collect expert judgment on what the expected value distributions each alternative would have for each objective, it may be desirable to sometimes
use data from literature instead. Using data from literature to acquire expected value distributions may have the potential of being viewed as more objective, which may improve the public acceptance of any final results, and is thus recommended for further study.

With the single-dimensional value functions, the fundamental objective weights, the distribution of expected values, and the subject matter expert weights every alternative nuclear fuel cycle can be evaluated. Further work and research still needs to determine whether one should aggregate the various weights and functions of participants to arrive at a group decision or aggregate the final values derived from participants.

With these two websites and their respective graphical user interfaces, the author is confident that the proposed MAUT based model can be of great use when assisting in the selection of a nuclear fuel cycle.

8.2 Monte Carlo Simulation

After all the data has been acquired to populate the various fields of the model from the two websites, simulations can be run to understand the spread of data and incorporate the uncertainty in the results. Specifically, Monte Carlo simulations can be run to sample from the distribution of weights on the subject matter experts, the weights on the different objectives, and the value distributions to include the uncertainty in the final results. Thus work needs to be done to develop a code with which this sampling can take place.

8.3 Correlations

Of potential interest would be to look at the data for subject matter experts and investigate if correlations exist based on different demographic factors or prefer-
ence for nuclear energy or other energy sources. These may potentially help identify participants or assure that no one group is biasing the results of the full analysis.

8.4 Research

Further research in the field of economics would undoubtedly assist in a better understanding of costs and accepted methods of comparing long-term, mid-term, and short-term costs and inflation. Additional research in survey psychology would greatly assist in developing the tools necessary to incorporate members of the general public into the decision. Finally, more research in the field of decision analysis would be very beneficial to the understanding of how to best operationalize MAUT style questions into a form that is readily answerable by members of the general public.
CHAPTER 9

CONCLUSION

9.1 Research Limitations

Although the subject matter expert weights that have been derived show good agreement between the different survey methodologies, it should be noted that there were slight differences in the surveys. First, the AHP based survey supplied definitions for each subject matter expert group, which could have lead to biasing some respondents. Second, the AHP survey asked which subject matter expert group was “more qualified in selecting a method of used nuclear fuel disposal,” while the multiscale survey asked “How qualified are each of the following information sources for nuclear waste disposal information.” This slight difference between the wording may have affected the weighting results in some manner.

A further limitation in the weighting of subject matter experts is that a relevant subject matter expert group may have been overlooked and omitted from the analysis. If this subject matter expert group is viewed as highly qualified by the general public then the resulting weights may change dramatically for the already evaluated subject matter experts. Thus the weights in this manuscript should only be taken within the context of those subject matter experts that were evaluated. The results from this analysis do not compare politicians, geologists, other types of engineers explicitly. What can only be stated with confidence is that nuclear engineers and scientists and environmental scientists are considered by the general public to be much more qualified compared to political scientists, economists, and other members of the general public. Although the author is confident that the subject matter experts under
evaluation were the most relevant; it is nonetheless a limitation of the research.

As with any MODA, there exists the possibility that a fundamental objective was errantly neglected from the MAUT based model, which could perhaps be of importance to the final decision. Hopefully, this potential is rather low since the model is on its third full revision; nonetheless, the possibility that an objective was omitted will always exist.

A further limitation involves the questions needed to populate the MAUT model. Although the MAUT based questions are more comprehensive and better thought out than AHP style pairwise comparisons, they may be more difficult to answer from the viewpoint of the general public. MAUT was developed working primarily in focus groups with a small number of highly motivated participants; however, our research involves eliciting preferences from a large group of relatively unmotivated survey respondents. Thus the wording of the MAUT based questions may not be ideal and may have to be altered to elicit meaningful values from members of the general public.

9.2 Use of MAUT versus AHP

That MAUT has been chosen as the preferred evaluation scheme over AHP has been done for a few reasons. The clarity test, fundamental objectives, and incorporating the range of objectives are techniques that are all derived from MAUT literature; however, this does not exclude the possibility of incorporating these techniques into an AHP analysis. The reason MAUT is still preferred has to primarily do with three factors: the tediousness of pairwise comparisons, the potential of rank reversal, and the accountability of the final results. When using MAUT the number of elicitations to determine the weights of objectives is the same as the number of comparisons; however, in AHP to completely populate a decision matrix the number of comparisons needed grows by Equation 2.2. This means that for an hierarchy with seven
objectives MAUT would require seven questions, while AHP would require 21. In the context of survey questions, if the same information can be derived with fewer questions the better; participants may be more motivated to complete the survey, may suffer less respondent fatigue, and a higher degree of confidence may be had in the results.

Furthermore, because AHP uses a matrix to derive the weights of objectives, specifically, because each element in a matrix is dependent on every other element of the matrix, there exists the possibility of rank reversal. An example of rank reversal would be if an AHP analysis was already completed and it was found that objective A was more important than objective B and that both were more important than objective C, i.e., \( A > B > C \). If after this analysis was complete, a new objective, objective D, was realized to be important and inserted into the analysis by performing pairwise comparisons with objectives A, B, and C; there exists the possibility of rank reversal of the original objectives. Meaning a possible outcome of the final ranking of the objectives, because of the matrix format, could be \( D > A > C > B \). Here the relative rank of objective B and objective C switched, as a result only of the introduction of objective D. Or put another way, if one preferred apples to bananas, and suddenly grapes were part of the analysis and they were preferred much less than either apples or bananas, because of the matrix format, there exists the possibility of now preferring bananas first, apples second, and grapes last. Thus it can be seen that rank reversal does not make logical sense; there is no reason why the introduction of a new unrelated term would cause preferences to switch.

Another problem with using the matrix format of AHP is that the results become inherently obscured from the inputs. Although it may be relatively simple mathematically to relate the matrix input to the final results, this may be difficult for members of the general public to understand and accept. MAUT’s swing weights
offer a much clear connection as to how the results tie directly with the inputs. For the understandability of any final report, it would be much clearer to present final swing weight values of MAUT as opposed to the pairwise comparison matrix format used in AHP. Thus since the same results can be obtained with MAUT using fewer elicitations, because there is no possibility of rank reversal using swing weights, and because swing weights allow for the results to be clearly tied to the inputs, there exists no reason in the mind of the author why AHP would be preferred to MAUT. As such, MAUT is the recommended elicitation methodology.

9.3 Contributions

The construction of a decision making model that includes public perceptions directly into its analysis represents a new approach to the selection of a nuclear fuel cycle for the United States. Although the original attempted model based on the AHP approach proved to be troublesome and is not recommended for further analysis, it is the hope of the author that this manuscript will allow this work move forward by providing a comprehensive description of what has been done, what has worked, and what has not worked. Specifically, it is with a high degree of confidence that the author recommends that the weights of subject matter experts should based on how the general public perceive them as qualified. In this manner, by incorporating nearly equally the input of nuclear engineers and scientists and environmental scientists and also communicating effectively that any decision is based on this hybrid approach, the general public may view a subsequently decided upon nuclear fuel cycle more favorably.

The actual important objectives and the values to populate those objectives for each alternative nuclear fuel cycle has not yet been tested with a thorough analysis. The objectives that were originally generated with the AHP approach seemed rea-
sonable at the time of their conception and creation; however, with the data received from surveys on the general public it became obvious that fundamental flaws were present in structuring objectives in this manner. With the knowledge of the clarity test and fundamental objectives, a relatively sound model has been created in Ch. 7 based on MAUT principles. Although this model has yet to be tested, with the strategy outlined in §8.1, the model is recommended by the author.

This research should be considered a learning opportunity and a confident step in the right direction, despite that a definitive nuclear fuel cycle has not been selected at the end of this analysis. This research gives the chance to consider the problem from multiple perspectives and gain a better understanding on what may be important for selecting a nuclear fuel cycle while incorporating public opinion.

It has been the author’s attempt to convey the results of this research with complete honesty and integrity; this is partly why so many appendices have been included. The author has not tried to force a result or prove something falsely. It is his hope that through reading this manuscript one may learn from what did and did not work and that one may be able to forward this research to its full fruition.
# Appendix A

## ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AHP</td>
<td>The Analytic Hierarchy Process</td>
</tr>
<tr>
<td>BOCR</td>
<td>Benefits, Opportunities, Costs, and Risks Analysis</td>
</tr>
<tr>
<td>DOE</td>
<td>Department of Energy</td>
</tr>
<tr>
<td>IAEA</td>
<td>International Atomic Energy Agency</td>
</tr>
<tr>
<td>INES</td>
<td>International Nuclear Event Scale</td>
</tr>
<tr>
<td>LWR</td>
<td>Light-water Reactor</td>
</tr>
<tr>
<td>MAUT</td>
<td>Multi-Attribute Utility Theory</td>
</tr>
<tr>
<td>MCDA</td>
<td>Multi-Criteria Decision Analysis</td>
</tr>
<tr>
<td>MODA</td>
<td>Multiple Objective Decision Analysis</td>
</tr>
<tr>
<td>MOX</td>
<td>Mixed-oxide Fuel</td>
</tr>
<tr>
<td>NFC</td>
<td>Nuclear Fuel Cycle</td>
</tr>
<tr>
<td>NRC</td>
<td>Nuclear Regulatory Commission</td>
</tr>
<tr>
<td>SD</td>
<td>Standard Deviation of the Sample</td>
</tr>
<tr>
<td>SDUF</td>
<td>Single-Dimensional Utility Function</td>
</tr>
<tr>
<td>SDVF</td>
<td>Single-Dimensional Value Function</td>
</tr>
<tr>
<td>SME</td>
<td>Subject Matter Expert</td>
</tr>
</tbody>
</table>
# Appendix B

## SYMBOLS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>A decision matrix populated with preferences $P_{i,j}$</td>
</tr>
<tr>
<td>$A'$</td>
<td>The decision matrix after being raised to a sufficiently high power</td>
</tr>
<tr>
<td>$A''$</td>
<td>The decision matrix after being normalized by the column summation vector</td>
</tr>
<tr>
<td>$a$</td>
<td>Some integer from 0 to $\gamma - 1$, used in generating the power scale</td>
</tr>
<tr>
<td>$B$</td>
<td>The value of the benefits hierarchy in a BOCR analysis</td>
</tr>
<tr>
<td>$b$</td>
<td>The balanced scale input values</td>
</tr>
<tr>
<td>$b'$</td>
<td>The column summation vector of the decision matrix</td>
</tr>
<tr>
<td>$C$</td>
<td>The value of the costs hierarchy in a BOCR analysis</td>
</tr>
<tr>
<td>$c$</td>
<td>The final priority vector of the criteria</td>
</tr>
<tr>
<td>$c''$</td>
<td>The row summation vector of the decision matrix</td>
</tr>
<tr>
<td>$\hat{c}_i$</td>
<td>The group priority for the $i^{th}$ criterion by using the geometric mean</td>
</tr>
<tr>
<td>$\bar{c}_i$</td>
<td>The group priority for the $i^{th}$ criterion by using the arithmetic mean</td>
</tr>
<tr>
<td>$c_{i,j}$</td>
<td>The priority of the $i^{th}$ criterion by the $j^{th}$ individual</td>
</tr>
<tr>
<td>$d''$</td>
<td>The elemental summation value of the row summation vector</td>
</tr>
<tr>
<td>$k$</td>
<td>A sufficiently large exponent to cause the decision matrix to converge</td>
</tr>
<tr>
<td>$m$</td>
<td>The number of individuals whose preferences are combined</td>
</tr>
<tr>
<td>$N$</td>
<td>The number of pairwise comparisons</td>
</tr>
<tr>
<td>$N_w$</td>
<td>The total number of possible weights, including interaction weights</td>
</tr>
<tr>
<td>$n$</td>
<td>The number of criteria or objectives under evaluation</td>
</tr>
<tr>
<td>$O$</td>
<td>The value of the opportunities hierarchy in a BOCR analysis</td>
</tr>
</tbody>
</table>
\( P_a \) The final additive with subtraction priority of an alternative in a BOCR analysis

\( P_m \) The final multiplicative priority of an alternative in a BOCR analysis

\( P \) The preference indicator used to compare alternatives

\( P_{i,j} \) The preference of the \( i^{th} \) criterion to the \( j^{th} \) criterion

\( p \) In two-ticket utility gambles, the probability that the objective will be at its best value

\( R \) The value of the risks hierarchy in a BOCR analysis

\( U_{A_j} \) The final utility of the \( j^{th} \) alternative, \( U_{A_j} = U_j \)

\( U_j \) The final utility of the \( j^{th} \) alternative, \( U_{A_j} = U_j \)

\( U_{A_j,O_i} \) The utility of the \( j^{th} \) alternative with respect to the \( i^{th} \) objective, \( U_{A_j,O_i} = U_j(x_i) \)

\( U_j(x_i) \) The utility of the \( j^{th} \) alternative with respect to the \( i^{th} \) objective, \( U_{A_j,O_i} = U_j(x_i) \)

\( V_{\text{max}} \) The maximum value of the range in question

\( V_{\text{min}} \) The minimum value of the range in question

\( V_{\text{(half|LR)}} \) The value at the half-range given that the lower-range is selected as the more important range

\( V_{\text{(half|UR)}} \) The value at the half-range given that the upper-range is selected as the more important range

\( V_1 \) The final value of NFC 1

\( V_2 \) The final value of NFC 2

\( V_j(O_i) \) The value which the \( j^{th} \) alternative takes for the \( i^{th} \) objective

\( V_j(O_{2a}) \) The value of the \( j^{th} \) alternative for the first costs objective

\( V_j(O_{2b}) \) The value of the \( j^{th} \) alternative for the second costs objective
\( V(O_i) \) The value of that every alternative takes for the \( i^{th} \) objective, if every alternative is equal with regards to the \( i^{th} \) objective.

\( w_1 \) The weight of objective 1

\( w_2 \) The weight of objective 2

\( w_{2a} \) The portion of weight that is dedicated toward the first costs objective

\( w_{2b} \) The portion of weight that is dedicated toward the second costs objective

\( w_b \) The weight of the benefits hierarchy in a BOCR analysis

\( w_c \) The weight of the costs hierarchy in a BOCR analysis

\( w_o \) The weight of the opportunities hierarchy in a BOCR analysis

\( w_r \) The weight of the risks hierarchy in a BOCR analysis

\( w_{O_i} \) The weight of the \( i^{th} \) objective, \( w_{O_i} = w_{x_i} \)

\( w_{x_i} \) The weight of the \( i^{th} \) objective, \( w_{O_i} = w_{x_i} \)

\( w_{ij} \) A bivariate interaction weight between the \( i^{th} \) objective by the \( j^{th} \) objective

\( x_b \) The balanced scale evaluation values

\( x_p \) The power scale evaluation values

\( Z \) The magnitude of importance that the selected half-range is over the other half-range

\( \gamma \) The number of increments of judgment used for comparing attributes (9)

\( \mu_a \) The arithmetic mean

\( \mu_g \) The geometric mean

\( \sigma_a \) The arithmetic standard deviation
\( \sigma_g \) The geometric standard deviation

\( \bar{\sigma}^2_{g(1)} \) The average geometric variance associated with the first objective derived from pairwise comparisons

\( \sigma^2_{g(1,j)} \) The geometric variance of the pairwise comparison of objective 1 with objective \( j \)

\( \omega_j \) The importance weight of the \( j^{th} \) individual
Note: Referenced equations can be found near the end of this appendix chapter.

Suppose a comprehensive evaluation of multiple nuclear fuel cycles has been undertaken, and only two objectives have been identified as fundamental. These objectives are Maximize Benefits and Minimize Costs. Within the range of all nuclear fuel cycles under evaluation, the range of benefits is from 0 to 10, evaluated in some arbitrary benefits unit. Assuming a linear value function for benefits, the metric-value pairs can be given as (0,0), (1,10), (2,20), … until (10,100). Additionally, the range of costs vary from $20 million to $0. Similarly, assuming a linear value function for costs, the metric-value pairs would be ($20M,0), ($19M,5), ($18M,10), … until ($0,100). These two value functions can be seen below in Figures 27 and 28.

Although other fuel cycles are under evaluation, during the course of the analysis it becomes relevant to compare two nuclear fuel cycles more closely; the fuel cycles are labeled Nuclear Fuel Cycle 1 (NFC 1) and Nuclear Fuel Cycle 2 (NFC 2). In terms of Maximize Benefits both NFC 1 and NFC 2 are rated a 10. However, in terms of Minimize Costs NFC 1 has overall more costs. Specifically, NFC 1 has total costs of $18M and NFC 2 has total costs of $17M. These inputs are summarized in the Table 47.

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Benefits</th>
<th>Total Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFC 1</td>
<td>10</td>
<td>$18M</td>
</tr>
<tr>
<td>NFC 2</td>
<td>10</td>
<td>$17M</td>
</tr>
</tbody>
</table>
Fig. 27. Benefits Value Function

Fig. 28. Total Costs Value Function
These inputs can be converted into decision value through the use of the value functions, giving the results shown in Table 48.

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Benefits (Value)</th>
<th>Total Costs (Value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFC 1</td>
<td>100</td>
<td>10</td>
</tr>
<tr>
<td>NFC 2</td>
<td>100</td>
<td>15</td>
</tr>
</tbody>
</table>

Applying weights to these objectives and summing the terms, the final value of each alternative can be found. Using Equation C.4 to determine the preference, the following figure, Figure 29, can be constructed by varying the weight of *Maximize Benefits*, i.e., $w_1$, from 0 to 1 and having the weight of the *Minimize Costs*, i.e., $w_2$, be the balance.

Fig. 29. Preference as a Function of the Weight of *Minimize Costs*
Recall from Equation C.2 and Equation C.3, that a positive value of $P$ means NFC 1 is preferred, a negative value of $P$ means that NFC 2 is preferred, and a zero value of $P$ means NFC 1 is equally preferred to NFC 2. From Figure 29 it is evident that there is no weighting scheme which would cause NFC 1 to be preferred over NFC 2 since the value of preference magnitude, $P$, is never positive. In fact, the only weight that would cause NFC 2 to not be preferred over NFC 1 is if the objective weight of Minimize Costs was set to zero, and thus the objective weight of Maximize Benefits would be set to 1, which results in NFC 1 being equally preferred to NFC 2.

However, again suppose that the same analysis was undertaken, but now the Minimize Costs objective is broken into two separate objectives, namely Minimize Facility Costs and Minimize Non-facility Costs, and that together these two costs objectives will sum to the total costs of each alternative nuclear fuel cycle. The range of the total costs still vary from $20$ million to $0$; however, each separate costs objective individually varies from $10$ million to $0$. Once again, assuming a linear value function for both costs objectives, the metric-value pairs would be $(10M,0)$, $(9M,10)$, $(8M,20)$, . . . until $(0,100)$. These two value functions can be seen below in Figures 30 and 31.

The total costs of each nuclear fuel cycle are the same as before, namely NFC 1 has costs of $18M and NFC 2 has total costs of $17M. However, when broken down further into facility and non-facility costs items, let us assume NFC 1 has facility costs of $10M and non-facility costs of $8M, while NFC 2 has facility costs of $8M and non-facility costs of $9M. These inputs can be seen in Table 49.

Using the value functions to convert these inputs into decision value we arrive at the values in Table 50.

Applying weights to these objectives and summing the terms, the final value of each alternative can be found. Using Equation C.10 to determine the preference, the
Fig. 30. Facility Costs Value Function

Fig. 31. Non-facility Costs Value Function
Table 49. Input Values for NFC 1 and NFC 2 for Separated Costs Objectives

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Benefits</th>
<th>Facility Costs</th>
<th>Non-facility Costs</th>
<th>Total Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFC 1</td>
<td>10</td>
<td>$10M</td>
<td>$8M</td>
<td>$18M</td>
</tr>
<tr>
<td>NFC 2</td>
<td>10</td>
<td>$8M</td>
<td>$9M</td>
<td>$17M</td>
</tr>
</tbody>
</table>

Table 50. Decision Values for NFC 1 and NFC 2 for Separated Costs Objectives

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Benefits (Value)</th>
<th>Facility Costs (Value)</th>
<th>Non-facility Costs (Value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFC 1</td>
<td>100</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>NFC 2</td>
<td>100</td>
<td>20</td>
<td>10</td>
</tr>
</tbody>
</table>

following figure, Figure 32, can be constructed by holding the weight of Maximize Benefits, i.e., $w_1$, constant at 0.5, having the weight of Minimize Facility Costs, i.e., $w_2$, vary from 0 to 0.5, and having the weight of Minimize Non-facility Costs be the balance.

Recall, once more, from Equation C.2 and Equation C.3, that a positive value of $P$ means NFC 1 is preferred, a negative value of $P$ means that NFC 2 is preferred, and a zero value of $P$ means NFC 1 is equally preferred to NFC 2. From Figure 32 it is evident that the choice of weights will in fact determine which nuclear fuel cycle is preferred. Specifically, given that Maximize Benefits is weighted as $w_1 = 0.5$, if the weight given to Maximize Facility Costs is less than one-sixth, $w_2 < 0.1667$, then NFC 1 will be preferred to NFC 2. Similarly, given that Maximize Benefits is weighted as $w_1 = 0.5$, if the weight given to Maximize Facility Costs is greater than one-sixth, $w_2 > 0.1667$, then NFC 2 will be preferred to NFC 1.

The result that the preference is dependent on the weights of the individual costs objectives is not dependent on the arbitrary selection of $w_1 = 0.5$, but exists
Fig. 32. Preference as a Function of the Weight of *Minimize Facility Costs* when \( w_1 = 0.5 \) regardless of the weight of *Maximize Benefits*. Two further cases of this can be seen in Figures 33 and 34.

The weights that lead to NFC 1 and NFC 2 being equally preferred are tabulated for five different cases in Table 51.

<table>
<thead>
<tr>
<th>Preference</th>
<th>Benefits Weight ( w_1 )</th>
<th>Facility Costs Weight ( w_{2a} )</th>
<th>Non-facility Costs Weight ( w_{2b} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFC 1 = NFC 2</td>
<td>0</td>
<td>0.3333</td>
<td>0.6667</td>
</tr>
<tr>
<td>NFC 1 = NFC 2</td>
<td>0.01</td>
<td>0.33</td>
<td>0.66</td>
</tr>
<tr>
<td>NFC 1 = NFC 2</td>
<td>0.5</td>
<td>0.1667</td>
<td>0.3333</td>
</tr>
<tr>
<td>NFC 1 = NFC 2</td>
<td>0.99</td>
<td>0.0033</td>
<td>0.0067</td>
</tr>
<tr>
<td>NFC 1 = NFC 2</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Fig. 33. Preference as a Function of the Weight of *Minimize Facility Costs* when $w_1 = 0.01$

Fig. 34. Preference as a Function of the Weight of *Minimize Facility Costs* when $w_1 = 0.99$
For each given $w_1$, if $w_{2a}$ is given any value less than those tabulated in Table 51, or equivalently, if $w_{2b}$ is given any value greater than those tabulated, then NFC 1 will be preferred to NFC 2. While both NFC 1 and NFC 2 have the same exact benefit, this preference of NFC 1 over NFC 2 is in spite of the fact that NFC 1 has higher total costs than NFC 2. This phenomenon of having the potential to prefer a more costly alternative despite everything else being equal is a direct consequence of weighting costs differently. To avoid this phenomenon completely, one must group all costs into a single item. This is the approach recommended by the author.

C.1 Equations

Note: The following equations and derivations are copied from Ch. 7, §7.3.1.1; they are included in this appendix for the reader’s benefit and so that the appendix may be self contained.

Presented next are the equations which give the final value of the two alternatives under consideration:

\[
V_1 = w_1V_1(O_1) + w_2V_1(O_2) \\
V_2 = w_1V_2(O_1) + w_2V_2(O_2)
\]  

(C.1)

where $V_1$ is the final value of NFC 1, $V_2$ is the final value of NFC 2, $w_1$ is the weight of objective 1, i.e., \textit{Maximize Benefits}, $w_2$ is the weight of objective 2, i.e., \textit{Minimize Costs}, and $V_j(O_i)$ is the value which the $j^{th}$ alternative takes for the $i^{th}$ objective.

If we want to understand which alternative is more preferred we can simply look at the difference between their final values such that:

\[
P = V_1 - V_2
\]  

(C.2)
\[
\begin{align*}
\text{if} & \quad \begin{cases} 
P > 0 & \text{NFC 1 is preferred} \\
0 & \text{NFC 1 is equal to NFC 2} \\
< 0 & \text{NFC 2 is preferred} 
\end{cases} \quad \text{(C.3)} \\
\text{where } P \text{ is the preference indicator used to compare alternatives.}
\end{align*}
\]

If we insert the equations from Equation C.1 into Equation C.2 we arrive at the following equation:

\[
P = V_1 - V_2
\]

\[
P = (w_1 V_1(O_1) + w_2 V_1(O_2)) - (w_1 V_2(O_1) + w_2 V_2(O_2)) \quad \text{(C.4)}
\]

Since both NFC 1 and NFC 2 have the same value with respect to \textit{Maximize Benefits}, i.e., 100, we can set both equal to the new term \(V(O_1)\):

\[
V_1(O_1) = V_2(O_1) = V(O_1) \quad \text{(C.5)}
\]

Substituting Equation C.5 into Equation C.4 we can simplify the preference indicator equation as:

\[
P = (w_1 V_1(O_1) + w_2 V_1(O_2)) - (w_1 V_2(O_1) + w_2 V_2(O_2))
\]

\[
P = w_1 V(O_1) + w_2 V_1(O_2) - w_1 V(O_1) - w_2 V_2(O_2)
\]

\[
P = w_2 V_1(O_2) - w_2 V_2(O_2)
\]

\[
P = w_2 (V_1(O_2) - V_2(O_2)) \quad \text{(C.6)}
\]

The result in Equation C.6 demonstrates that the final preference between the two alternatives is a function only of the difference in how well each alternative is valued in terms of the second objective, namely \textit{Minimize Costs}. As the weights of objectives can only take positive values, the choice of weights will never switch the preference; rather the weights will only determine the magnitude of the preference.
Thus when everything else is equal, NFC 1 will always be preferred if its total cost is less than NFC 2, i.e., \( V_1(O_2) \) will be greater than \( V_2(O_2) \) resulting in \( P > 0 \). Likewise, NFC 2 will always be preferred if its total cost is less than NFC 1, i.e., \( V_2(O_2) \) will be greater than \( V_1(O_2) \) resulting in \( P < 0 \).

However, suppose now that the same analysis was undertaken but instead of costs being combined into one item, it was thought that Minimize Costs should really be broken into two separate objectives such that:

\[
\begin{align*}
    w_2 &= w_{2a} + w_{2b} \\
    O_2 &= O_{2a} + O_{2b}
\end{align*}
\]  

(C.7)  

(C.8)

where \( w_{2a} \) represents the portion of weight that is dedicated toward the first costs objective, \( w_{2b} \) represents the portion of weight that is dedicated toward the second costs objective, \( O_2 \) is the original costs objective’s measured value, \( O_{2a} \) is first costs objectives measured value, and \( O_{2b} \) is second costs objectives measured value. Thus \( V_j(O_{2a}) \) is the value of the \( j^{th} \) alternative for the first costs objective, and \( V_j(O_{2b}) \) is the value of the \( j^{th} \) alternative for the second costs objective. Let us suppose the first costs objective is Minimize Facility Costs and the second is Minimize Non-facility Costs. The equations for deriving the final value of each alternative are now given as follows:

\[
\begin{align*}
    V_1 &= w_1 V_1(O_1) + w_{2a} V_1(O_{2a}) + w_{2b} V_1(O_{2b}) \\
    V_2 &= w_1 V_2(O_1) + w_{2a} V_2(O_{2a}) + w_{2b} V_2(O_{2b})
\end{align*}
\]  

(C.9)

To determine the preference of which alternative, we can substitute Equation
C.9 into Equation C.2; giving the following equation:

\[ P = V_1 - V_2 \]

\[ P = (w_1 V_1(O_1) + w_2a V_1(O_{2a}) + w_2b V_1(O_{2b})) - (w_1 V_2(O_1) + w_2a V_2(O_{2a}) + w_2b V_2(O_{2b})) \]  
(C.10)

Since NFC 1 and NFC 2 both have the same value in terms of benefits, we can once again substitute in Equation C.5. This leads to the following simplified equation:

\[ P = (w_1 V_1(O_1) + w_2a V_1(O_{2a}) + w_2b V_1(O_{2b})) - (w_1 V_2(O_1) + w_2a V_2(O_{2a}) + w_2b V_2(O_{2b})) \]

\[ P = (w_1 V_1(O_1) + w_2a V_1(O_{2a}) + w_2b V_1(O_{2b})) - (w_1 V_1(O_1) + w_2a V_2(O_{2a}) + w_2b V_2(O_{2b})) \]

\[ P = w_2a V_1(O_{2a}) + w_2b V_1(O_{2b}) - w_2a V_2(O_{2a}) - w_2b V_2(O_{2b}) \]

\[ P = w_2a (V_1(O_{2a}) - V_2(O_{2a})) + w_2b (V_1(O_{2b}) - V_2(O_{2b})) \]  
(C.11)
Appendix D

GEOMETRIC MEAN AND STANDARD DEVIATION

Normally to find a number which can represent the expected value of a distribution of values, an average can be taken. Which is simply from Equation D.1:

\[ \mu_a = \frac{\sum_{i=1}^{n} x_i}{n} \]  

(D.1)

where \( \mu_a \) represents the average, \( x \) represents a specific value, and \( n \) is the total number of values under consideration. Another name for this expected value is the arithmetic mean, hence the subscript \( a \).

Similarly, when we want to understand the distribution of the data, a number which can represent the spread of values, a standard deviation can be found. This is simply from Equation D.2:

\[ \sigma_a = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \mu_a)^2}{n - 1}} \]  

(D.2)

where \( \sigma_a \) represents the sample standard deviation. Another name for this type of spread parameter is the arithmetic standard deviation, hence the subscript \( a \).

If the data follows a normal Gaussian distribution then a good understanding of the spread of the data can be derived by simply stating the arithmetic mean plus or minus the arithmetic standard deviation. Within this range, 68.2% of all values can be found see Figure 35. This range is shown in Equation D.3:

\[ \mu_a \pm \sigma_a \]  

(D.3)
However, what if the distribution of data does not follow this normal Gaussian distribution? Are these parameters for the expected value and the expected spread still valid? Strictly speaking, they are not. Of concern to us is when the data follows a geometric, or “log-normal,” distribution. For this sort of distribution we can describe the expected value and the expected spread by two parameters again, first the geometric mean, and secondly the geometric standard deviation. To calculate the geometric mean we simply use either Equation D.4 or D.5, as they are equivalent [23]:

\[
\mu_g = \left( \prod_{i=1}^{n} x_i \right)^{\frac{1}{n}}
\]

\[\text{(D.4)}\]
where $\mu_g$ denotes the geometric mean, and ‘antilog($y$)’ means the same as ten raised to the power of $y$.

Additionally, to find the standard deviation of the geometric distribution one can simply use Equation D.6 [23].

$$\sigma_g = \text{antilog} \left[ \sqrt{\frac{\sum_{i=1}^{n} \log(x_i)^2}{n} - \left( \frac{\sum_{i=1}^{n} \log(x_i)}{n} \right)^2} \right]$$  \hspace{1cm} (D.6)

where $\sigma_g$ denotes the geometric standard deviation.

As the arithmetic standard deviation describes the spread of the data in the normal distribution by adding or subtracting it from the arithmetic mean, the geometric standard deviation describes the spread of the data in the geometric distribution by multiplying or dividing it from the geometric mean [23]. Likewise 68.2% of the all values of the geometric distribution can be found by the geometric mean multiplied or divided by the geometric standard deviation [23]. This can be seen in Equation D.7.

$$\mu_g \times \sigma_g \text{ or } \mu_g \div \sigma_g$$  \hspace{1cm} (D.7)

Within this range 68.2% of the values will be found, see Figure 36 for the graphical representation.
Fig. 36. Geometric “Log-Normal” Distribution
## RESULTS FROM THE LARGE NUCLEAR ENGINEERING AND SCIENCE CONFERENCE

Table 52. Objective Weights from the Large Nuclear Engineering and Science Conference

<table>
<thead>
<tr>
<th>Survey</th>
<th>Objective</th>
<th>Weight</th>
<th>Rank Change</th>
<th>Objective</th>
<th>Weight</th>
<th>Weight Change</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>All Participants Included</td>
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<td></td>
<td>10% Inconsistency Threshold</td>
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<td></td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nuclear Political Stability</td>
<td>24.83%</td>
<td>=</td>
<td>Nuclear Political Stability</td>
<td>29.64%</td>
<td>+4.81%</td>
</tr>
<tr>
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<td>Legal Resolution</td>
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<td>=</td>
<td>Legal Resolution</td>
<td>17.08%</td>
<td>-4.66%</td>
</tr>
<tr>
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<td>14.47%</td>
<td>=</td>
<td>Pollution &amp; Emissions Reduction</td>
<td>10.83%</td>
<td>-3.64%</td>
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<td>Fuel Requirement Reduction</td>
<td>10.00%</td>
<td>+0.70%</td>
</tr>
<tr>
<td></td>
<td>Fuel Requirement Reduction</td>
<td>7.99%</td>
<td>-1</td>
<td>Local Improvements</td>
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<td>0.04%</td>
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<tr>
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<td>Infrastructure Development</td>
<td>6.00%</td>
<td>-0.97%</td>
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<tr>
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<td><strong>Costs</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>Licensing</td>
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<td>Facility Construction &amp; Maintenance</td>
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<td>+1.00%</td>
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<td>19.40%</td>
<td>+1.74%</td>
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<td>Technology Development</td>
<td>14.59%</td>
<td>-2.04%</td>
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<td>Energy Policy Leadership</td>
<td>14.55%</td>
<td>-1.46%</td>
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<td>U.S. Government Competence</td>
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<td>-1.29%</td>
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<td>+0.60%</td>
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<td>Public Perception</td>
<td>42.69%</td>
<td>+14.77%</td>
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<td>Waste Escape Accidents</td>
<td>18.23%</td>
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<td>Potential Future Burden</td>
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<td>-0.77%</td>
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<td>Proliferation Potential</td>
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<td>-2.28%</td>
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</table>
## Appendix F

### AVERAGE GEOMETRIC VARIANCE FOR INITIAL SURVEYS

Table 53. Average Geometric Variance for each Objective

<table>
<thead>
<tr>
<th>Survey</th>
<th>Objective</th>
<th>No Threshold</th>
<th>20% Inconsistency</th>
<th>15% Inconsistency</th>
<th>10% Inconsistency</th>
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<td><strong>Benefits</strong></td>
<td>Disposition Flexibility</td>
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<td>2.56</td>
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<td>Legal Resolution</td>
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<td>4.57</td>
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</tr>
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<td>Local Improvements</td>
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<td>2.87</td>
<td>2.73</td>
</tr>
<tr>
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<td>Nuclear Political Stability</td>
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<td>3.77</td>
<td>3.77</td>
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<td>Pollution &amp; Emissions Reduction</td>
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<td>3.67</td>
<td>3.67</td>
<td>5.84</td>
</tr>
<tr>
<td><strong>Costs</strong></td>
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<td>1.99</td>
<td>1.63</td>
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<td>1.47</td>
<td>1.27</td>
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<tr>
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<td>Energy Policy Leadership</td>
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<td>2.12</td>
<td>1.40</td>
</tr>
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<td>1.74</td>
<td>1.92</td>
<td>1.90</td>
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<td>3.17</td>
<td>2.35</td>
<td>2.13</td>
<td>1.50</td>
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<tr>
<td></td>
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<td>2.17</td>
</tr>
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<td>8.20</td>
<td>5.58</td>
<td>6.55</td>
<td>2.78</td>
</tr>
<tr>
<td></td>
<td>Potential Future Burden</td>
<td>5.23</td>
<td>5.68</td>
<td>5.09</td>
<td>5.63</td>
</tr>
<tr>
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<td>Proliferation Potential</td>
<td>4.38</td>
<td>2.37</td>
<td>2.47</td>
<td>2.42</td>
</tr>
<tr>
<td></td>
<td>Public Perception</td>
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<td>4.13</td>
<td>2.64</td>
<td>1.18</td>
</tr>
<tr>
<td></td>
<td>Radiotoxicity</td>
<td>3.90</td>
<td>3.07</td>
<td>2.97</td>
<td>2.26</td>
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<td>Supply Availability</td>
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<td>3.29</td>
<td>2.06</td>
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<td>Waste Escape Accidents</td>
<td>5.66</td>
<td>5.91</td>
<td>6.09</td>
<td>5.65</td>
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</tbody>
</table>
Appendix G

FREQUENCY TABLES FOR SUBJECT MATTER EXPERTS SIMPLE RANKINGS

<table>
<thead>
<tr>
<th>Ranking</th>
<th>Economists</th>
<th>Environmental Scientists</th>
<th>Nuclear Engineers and Scientists</th>
<th>Political Scientists</th>
<th>The General Public</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>53</td>
<td>41</td>
<td>1</td>
<td>6</td>
</tr>
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<td>4</td>
</tr>
<tr>
<td>3</td>
<td>40</td>
<td>5</td>
<td>2</td>
<td>34</td>
<td>23</td>
</tr>
<tr>
<td>4</td>
<td>44</td>
<td>4</td>
<td>4</td>
<td>37</td>
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<td>14</td>
<td>2</td>
<td>4</td>
<td>28</td>
<td>56</td>
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Table 54. Frequency Table of Number of Responses for Simple Ranking
<table>
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<tr>
<th>Response</th>
<th>Economists</th>
<th>Environmental Scientists</th>
<th>Nuclear Engineers and Scientists</th>
<th>Political Scientists</th>
<th>The General Public</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not Qualified at All</td>
<td>238</td>
<td>21</td>
<td>16</td>
<td>262</td>
<td>317</td>
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<tr>
<td>A Little Bit Qualified</td>
<td>114</td>
<td>25</td>
<td>9</td>
<td>119</td>
<td>125</td>
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<tr>
<td>Somewhat Qualified</td>
<td>90</td>
<td>71</td>
<td>65</td>
<td>84</td>
<td>41</td>
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<tr>
<td>Qualified</td>
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<td>196</td>
<td>143</td>
<td>23</td>
<td>8</td>
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<td>184</td>
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Table 55. Frequency Table of Number of Responses for Qualifications Question

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<th>Nuclear Engineers and Scientists</th>
<th>Political Scientists</th>
<th>The General Public</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not Honest at All</td>
<td>120</td>
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<td>26</td>
<td>218</td>
<td>133</td>
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<tr>
<td>A Little Bit Honest</td>
<td>144</td>
<td>53</td>
<td>48</td>
<td>148</td>
<td>160</td>
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<tr>
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<td>135</td>
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<td>68</td>
<td>168</td>
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Table 56. Frequency Table of Number of Responses for Honesty Question
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<th>Nuclear Engineers and Scientists</th>
<th>Political Scientists</th>
<th>The General Public</th>
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<td>142</td>
<td>128</td>
</tr>
<tr>
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<td>123</td>
<td>84</td>
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<td>70</td>
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</table>

Table 57. Frequency Table of Number of Responses for Accessibility Question

<table>
<thead>
<tr>
<th>Response</th>
<th>Economists</th>
<th>Environmental Scientists</th>
<th>Nuclear Engineers and Scientists</th>
<th>Political Scientists</th>
<th>The General Public</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not Understandable at All</td>
<td>132</td>
<td>63</td>
<td>84</td>
<td>152</td>
<td>145</td>
</tr>
<tr>
<td>A Little Bit Understandable</td>
<td>160</td>
<td>128</td>
<td>143</td>
<td>142</td>
<td>138</td>
</tr>
<tr>
<td>Somewhat Understandable</td>
<td>144</td>
<td>158</td>
<td>167</td>
<td>130</td>
<td>130</td>
</tr>
<tr>
<td>Understandable</td>
<td>55</td>
<td>117</td>
<td>73</td>
<td>60</td>
<td>64</td>
</tr>
<tr>
<td>Very Understandable</td>
<td>6</td>
<td>31</td>
<td>26</td>
<td>14</td>
<td>18</td>
</tr>
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</table>

Table 58. Frequency Table of Number of Responses for Understandability Question
## Appendix H

### FREQUENCY TABLES FOR OBJECTIVES SIMPLE RANKINGS

<table>
<thead>
<tr>
<th>Benefits Objective</th>
<th>Rank</th>
<th>Rank</th>
<th>Rank</th>
<th>Rank</th>
<th>Rank</th>
<th>Rank</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disposal Flexibility</td>
<td>13</td>
<td>17</td>
<td>18</td>
<td>13</td>
<td>9</td>
<td>13</td>
<td>10</td>
</tr>
<tr>
<td>Fuel Requirement Reduction</td>
<td>24</td>
<td>21</td>
<td>11</td>
<td>13</td>
<td>7</td>
<td>11</td>
<td>6</td>
</tr>
<tr>
<td>National Infrastructure Development</td>
<td>7</td>
<td>10</td>
<td>17</td>
<td>12</td>
<td>15</td>
<td>14</td>
<td>18</td>
</tr>
<tr>
<td>Legal Resolution</td>
<td>9</td>
<td>10</td>
<td>9</td>
<td>12</td>
<td>17</td>
<td>17</td>
<td>19</td>
</tr>
<tr>
<td>Local Economic Development</td>
<td>16</td>
<td>11</td>
<td>13</td>
<td>22</td>
<td>14</td>
<td>11</td>
<td>6</td>
</tr>
<tr>
<td>Public &amp; Political Acceptance</td>
<td>14</td>
<td>9</td>
<td>12</td>
<td>12</td>
<td>14</td>
<td>15</td>
<td>17</td>
</tr>
<tr>
<td>Increase Technical Workforce</td>
<td>10</td>
<td>15</td>
<td>13</td>
<td>9</td>
<td>17</td>
<td>12</td>
<td>17</td>
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</table>

Table 59. Frequency Table of Benefits Objectives for Simple Ranking

<table>
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<tr>
<th>Costs Objective</th>
<th>Rank</th>
<th>Rank</th>
<th>Rank</th>
<th>Rank</th>
<th>Rank</th>
<th>Rank</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facility Construction, Operation, &amp;</td>
<td>19</td>
<td>14</td>
<td>12</td>
<td>6</td>
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<td>7</td>
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<tr>
<td>Maintenance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Legal Fees &amp; Fines</td>
<td>3</td>
<td>9</td>
<td>4</td>
<td>12</td>
<td>14</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>Licensing</td>
<td>3</td>
<td>6</td>
<td>5</td>
<td>11</td>
<td>9</td>
<td>12</td>
<td>24</td>
</tr>
<tr>
<td>Proliferation Prevention</td>
<td>22</td>
<td>9</td>
<td>12</td>
<td>7</td>
<td>10</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Supplemental Infrastructure Development</td>
<td>10</td>
<td>9</td>
<td>16</td>
<td>11</td>
<td>12</td>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td>Switching Policy</td>
<td>7</td>
<td>9</td>
<td>10</td>
<td>11</td>
<td>9</td>
<td>16</td>
<td>8</td>
</tr>
<tr>
<td>Transportation</td>
<td>6</td>
<td>14</td>
<td>11</td>
<td>12</td>
<td>9</td>
<td>8</td>
<td>10</td>
</tr>
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</table>

Table 60. Frequency Table of Costs Objectives for Simple Ranking

188
<table>
<thead>
<tr>
<th>Opportunities Objective</th>
<th>Rank 1</th>
<th>Rank 2</th>
<th>Rank 3</th>
<th>Rank 4</th>
<th>Rank 5</th>
<th>Rank 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>American Economic Development</td>
<td>13</td>
<td>22</td>
<td>20</td>
<td>21</td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td>Energy Policy Leadership</td>
<td>4</td>
<td>14</td>
<td>16</td>
<td>17</td>
<td>29</td>
<td>12</td>
</tr>
<tr>
<td>Long-term Electricity Production</td>
<td>32</td>
<td>19</td>
<td>17</td>
<td>16</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>New Technology Development</td>
<td>24</td>
<td>18</td>
<td>15</td>
<td>11</td>
<td>15</td>
<td>9</td>
</tr>
<tr>
<td>Nuclear Industry Growth</td>
<td>6</td>
<td>17</td>
<td>15</td>
<td>22</td>
<td>18</td>
<td>14</td>
</tr>
<tr>
<td>U.S. Government Competence</td>
<td>13</td>
<td>2</td>
<td>9</td>
<td>5</td>
<td>15</td>
<td>48</td>
</tr>
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</table>

Table 61. Frequency Table of Opportunities Objectives for Simple Ranking

<table>
<thead>
<tr>
<th>Risks Objective</th>
<th>Rank 1</th>
<th>Rank 2</th>
<th>Rank 3</th>
<th>Rank 4</th>
<th>Rank 5</th>
<th>Rank 6</th>
<th>Rank 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accidents or Nuclear Material Release</td>
<td>17</td>
<td>29</td>
<td>21</td>
<td>6</td>
<td>10</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Potential Future Burden</td>
<td>12</td>
<td>15</td>
<td>22</td>
<td>19</td>
<td>2</td>
<td>12</td>
<td>2</td>
</tr>
<tr>
<td>Proliferation Potential</td>
<td>8</td>
<td>11</td>
<td>5</td>
<td>20</td>
<td>15</td>
<td>16</td>
<td>9</td>
</tr>
<tr>
<td>Public or Political Rejection</td>
<td>5</td>
<td>8</td>
<td>5</td>
<td>8</td>
<td>21</td>
<td>18</td>
<td>19</td>
</tr>
<tr>
<td>Radiation Exposure</td>
<td>32</td>
<td>14</td>
<td>15</td>
<td>8</td>
<td>6</td>
<td>9</td>
<td>0</td>
</tr>
<tr>
<td>Supply Availability</td>
<td>8</td>
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<td>8</td>
<td>16</td>
<td>16</td>
<td>20</td>
<td>11</td>
</tr>
<tr>
<td>Technical Feasibility</td>
<td>2</td>
<td>2</td>
<td>8</td>
<td>7</td>
<td>14</td>
<td>9</td>
<td>42</td>
</tr>
</tbody>
</table>

Table 62. Frequency Table of Risks Objectives for Simple Ranking
Table 63. Sample Sizes of Surveys Collected from the General Public with Integer Interpretation

<table>
<thead>
<tr>
<th>Survey</th>
<th>Sample Size</th>
<th>No Threshold</th>
<th>20% Inconsistency</th>
<th>15% Inconsistency</th>
<th>10% Inconsistency</th>
<th>Percent Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experts</td>
<td>100</td>
<td>82</td>
<td>74</td>
<td>54</td>
<td>46</td>
<td>46%</td>
</tr>
<tr>
<td>Benefits</td>
<td>87</td>
<td>55</td>
<td>46</td>
<td>34</td>
<td>61%</td>
<td></td>
</tr>
<tr>
<td>Costs</td>
<td>70</td>
<td>44</td>
<td>37</td>
<td>25</td>
<td>64%</td>
<td></td>
</tr>
<tr>
<td>Opportunities</td>
<td>86</td>
<td>60</td>
<td>47</td>
<td>38</td>
<td>56%</td>
<td></td>
</tr>
<tr>
<td>Risks</td>
<td>84</td>
<td>55</td>
<td>42</td>
<td>33</td>
<td>61%</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>427</td>
<td>296</td>
<td>246</td>
<td>184</td>
<td>57%</td>
<td></td>
</tr>
</tbody>
</table>
## Table 64. Subject Matter Expert and Objective Weights from General Public using Normalized Geometric Mean and Integer Interpretation

<table>
<thead>
<tr>
<th>Survey</th>
<th>SME / Objective</th>
<th>All Participants Included</th>
<th>Weight</th>
<th>Rank Change</th>
<th>10% Inconsistency Threshold</th>
<th>Weight</th>
<th>Weight Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experts</td>
<td>Nuclear Engineers &amp; Scientists</td>
<td>38.60%</td>
<td>=</td>
<td>Nuclear Engineers &amp; Scientists</td>
<td>37.82%</td>
<td>-0.78%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Environmental Scientists</td>
<td>36.26%</td>
<td>=</td>
<td>Environmental Scientists</td>
<td>37.80%</td>
<td>+1.54%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Economists</td>
<td>9.37%</td>
<td>=</td>
<td>Economists</td>
<td>8.83%</td>
<td>-0.54%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Political Scientists</td>
<td>8.49%</td>
<td>=</td>
<td>Political Scientists</td>
<td>8.62%</td>
<td>+0.13%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>The General Public</td>
<td>7.28%</td>
<td>=</td>
<td>The General Public</td>
<td>6.93%</td>
<td>-0.35%</td>
<td></td>
</tr>
<tr>
<td>Benefits</td>
<td>Fuel Requirement Reduction</td>
<td>20.68%</td>
<td>=</td>
<td>Fuel Requirement Reduction</td>
<td>22.61%</td>
<td>+1.93%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Disposal Flexibility</td>
<td>17.17%</td>
<td>=</td>
<td>Disposal Flexibility</td>
<td>17.47%</td>
<td>+0.30%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Local Economic Development</td>
<td>14.46%</td>
<td>+1</td>
<td>National Infrastructure Development</td>
<td>14.67%</td>
<td>+0.21%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>National Infrastructure Development</td>
<td>14.76%</td>
<td>-1</td>
<td>Local Economic Development</td>
<td>14.62%</td>
<td>+0.14%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Increase Technical Workforce</td>
<td>12.56%</td>
<td>=</td>
<td>Increase Technical Workforce</td>
<td>11.85%</td>
<td>-0.71%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Public &amp; Political Acceptance</td>
<td>10.95%</td>
<td>=</td>
<td>Public &amp; Political Acceptance</td>
<td>9.63%</td>
<td>-1.32%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Legal Resolution</td>
<td>10.30%</td>
<td>=</td>
<td>Legal Resolution</td>
<td>9.16%</td>
<td>-1.14%</td>
<td></td>
</tr>
<tr>
<td>Costs</td>
<td>Proliferation Prevention</td>
<td>28.96%</td>
<td>+1</td>
<td>Facility Construction, Operation, &amp; Maintenance</td>
<td>20.55%</td>
<td>-8.41%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Facility Construction, Operation, &amp; Maintenance</td>
<td>20.82%</td>
<td>-1</td>
<td>Proliferation Prevention</td>
<td>18.81%</td>
<td>-2.01%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Supplemental Infrastructure Development</td>
<td>14.17%</td>
<td>=</td>
<td>Supplemental Infrastructure Development</td>
<td>15.06%</td>
<td>+0.89%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Transportation</td>
<td>13.07%</td>
<td>=</td>
<td>Transportation</td>
<td>14.67%</td>
<td>+1.60%</td>
<td></td>
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<tr>
<td></td>
<td>Switching Policy</td>
<td>11.93%</td>
<td>=</td>
<td>Switching Policy</td>
<td>13.77%</td>
<td>+1.84%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Legal Fees &amp; Fines</td>
<td>10.13%</td>
<td>+1</td>
<td>Licensing</td>
<td>8.77%</td>
<td>-0.17%</td>
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</tr>
<tr>
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<td>Licensing</td>
<td>8.94%</td>
<td>-1</td>
<td>Legal Fees &amp; Fines</td>
<td>8.43%</td>
<td>-0.51%</td>
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</tr>
<tr>
<td>Opportunities</td>
<td>Long-term Energy Production</td>
<td>21.88%</td>
<td>=</td>
<td>Long-term Energy Production</td>
<td>25.27%</td>
<td>+3.39%</td>
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</tr>
<tr>
<td></td>
<td>American Economic Development</td>
<td>26.45%</td>
<td>+1</td>
<td>New Technology Development</td>
<td>20.97%</td>
<td>-5.48%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>New Technology Development</td>
<td>26.12%</td>
<td>-1</td>
<td>American Economic Development</td>
<td>20.77%</td>
<td>-5.35%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Energy Policy Leadership</td>
<td>12.56%</td>
<td>+1</td>
<td>U.S. Government Competence</td>
<td>11.26%</td>
<td>-1.30%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>U.S. Government Competence</td>
<td>11.77%</td>
<td>+1</td>
<td>Nuclear Industry Growth</td>
<td>11.09%</td>
<td>+0.68%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nuclear Industry Growth</td>
<td>9.97%</td>
<td>-2</td>
<td>Energy Policy Leadership</td>
<td>10.73%</td>
<td>+0.76%</td>
<td></td>
</tr>
<tr>
<td>Risks</td>
<td>Accidents or Nuclear Material Release</td>
<td>26.04%</td>
<td>+1</td>
<td>Radiation Exposure</td>
<td>27.19%</td>
<td>+2.15%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Radiation Exposure</td>
<td>25.18%</td>
<td>-1</td>
<td>Accidents or Nuclear Material Release</td>
<td>26.89%</td>
<td>+1.71%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Potential Future Burden</td>
<td>14.88%</td>
<td>=</td>
<td>Potential Future Burden</td>
<td>14.99%</td>
<td>+0.11%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Proliferation Potential</td>
<td>11.18%</td>
<td>=</td>
<td>Proliferation Potential</td>
<td>10.12%</td>
<td>-1.06%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Technical Feasibility</td>
<td>8.88%</td>
<td>=</td>
<td>Technical Feasibility</td>
<td>7.95%</td>
<td>-0.93%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Supply Availability</td>
<td>7.20%</td>
<td>=</td>
<td>Supply Availability</td>
<td>7.32%</td>
<td>+0.12%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Public or Political Rejection</td>
<td>6.65%</td>
<td>=</td>
<td>Public or Political Rejection</td>
<td>5.83%</td>
<td>-0.82%</td>
<td></td>
</tr>
</tbody>
</table>
### Appendix J

**AHP: BALANCED INTERPRETATION**

Table 65. Sample Sizes of Surveys Collected from the General Public with Balanced Interpretation

<table>
<thead>
<tr>
<th>Survey</th>
<th>Sample Size</th>
<th>No Threshold</th>
<th>20% Inconsistency</th>
<th>15% Inconsistency</th>
<th>10% Inconsistency</th>
<th>Percent Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experts</td>
<td>100</td>
<td>68</td>
<td>61</td>
<td>49</td>
<td>51%</td>
<td></td>
</tr>
<tr>
<td>Benefits</td>
<td>87</td>
<td>68</td>
<td>63</td>
<td>48</td>
<td>45%</td>
<td></td>
</tr>
<tr>
<td>Costs</td>
<td>70</td>
<td>52</td>
<td>49</td>
<td>40</td>
<td>43%</td>
<td></td>
</tr>
<tr>
<td>Opportunities</td>
<td>86</td>
<td>61</td>
<td>57</td>
<td>41</td>
<td>52%</td>
<td></td>
</tr>
<tr>
<td>Risks</td>
<td>84</td>
<td>63</td>
<td>55</td>
<td>40</td>
<td>52%</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>427</td>
<td>312</td>
<td>285</td>
<td>218</td>
<td>49%</td>
<td></td>
</tr>
</tbody>
</table>
Table 66. Subject Matter Expert and Objective Weights from General Public using Normalized Geometric Mean and Balanced Interpretation

<table>
<thead>
<tr>
<th>Survey</th>
<th>SME/Objective</th>
<th>Weight</th>
<th>Rank Change</th>
<th>Objective</th>
<th>Weight</th>
<th>Weight Change</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SME /Objective</td>
<td>Rank Change</td>
<td>Objective</td>
<td>Weight</td>
<td>Weight Change</td>
<td></td>
</tr>
<tr>
<td>Experts</td>
<td>Nuclear Engineers &amp; Scientists</td>
<td>36.15%</td>
<td>=</td>
<td>Nuclear Engineers &amp; Scientists</td>
<td>37.59%</td>
<td>+1.44%</td>
</tr>
<tr>
<td></td>
<td>Environmental Scientists</td>
<td>33.05%</td>
<td>=</td>
<td>Environmental Scientists</td>
<td>31.23%</td>
<td>-1.82%</td>
</tr>
<tr>
<td></td>
<td>Economists</td>
<td>11.24%</td>
<td>=</td>
<td>Economists</td>
<td>11.60%</td>
<td>+0.36%</td>
</tr>
<tr>
<td></td>
<td>Political Scientists</td>
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<td>=</td>
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<td>8.59%</td>
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<tr>
<td>Benefits</td>
<td>Fuel Requirement Reduction</td>
<td>18.39%</td>
<td>=</td>
<td>Fuel Requirement Reduction</td>
<td>17.90%</td>
<td>-0.49%</td>
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<tr>
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<td>-0.22%</td>
</tr>
<tr>
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<td>Licensing</td>
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<td>=</td>
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<td>-0.01%</td>
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<td>-0.89%</td>
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<td>Proliferation Potential</td>
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<td>+0.45%</td>
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<td>Supply Availability</td>
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<td>Public or Political Rejection</td>
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</tbody>
</table>
Appendix K

AHP: POWER INTERPRETATION

Table 67. Sample Sizes of Surveys Collected from the General Public with Power Interpretation

<table>
<thead>
<tr>
<th>Survey</th>
<th>Sample Size</th>
<th>20% Inconsistency</th>
<th>15% Inconsistency</th>
<th>10% Inconsistency</th>
<th>Percent Reduction</th>
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<tbody>
<tr>
<td>Experts</td>
<td>100</td>
<td>80</td>
<td>71</td>
<td>58</td>
<td>42%</td>
</tr>
<tr>
<td>Benefits</td>
<td>87</td>
<td>70</td>
<td>63</td>
<td>49</td>
<td>44%</td>
</tr>
<tr>
<td>Costs</td>
<td>70</td>
<td>52</td>
<td>49</td>
<td>40</td>
<td>43%</td>
</tr>
<tr>
<td>Opportunities</td>
<td>86</td>
<td>64</td>
<td>62</td>
<td>48</td>
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<td>Risks</td>
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<td>58</td>
<td>43</td>
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<tr>
<td>Total</td>
<td>427</td>
<td>329</td>
<td>303</td>
<td>238</td>
<td>44%</td>
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Table 68. Subject Matter Expert and Objective Weights from General Public using Normalized Geometric Mean and Power Interpretation

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<thead>
<tr>
<th>Survey</th>
<th>Objective</th>
<th>Weight</th>
<th>Rank Change</th>
<th>Weight</th>
<th>Weight Change</th>
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<td>Experts</td>
<td>Nuclear Engineers &amp; Scientists</td>
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<td>33.57%</td>
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<tr>
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<td>Economists</td>
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<td>=</td>
<td>10.49%</td>
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<tr>
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<td>Political Scientists</td>
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<td>=</td>
<td>9.88%</td>
<td>+0.15%</td>
</tr>
<tr>
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<td>The General Public</td>
<td>8.57%</td>
<td>=</td>
<td>8.20%</td>
<td>-0.37%</td>
</tr>
<tr>
<td>Benefits</td>
<td>Fuel Requirement Reduction</td>
<td>19.07%</td>
<td>=</td>
<td>18.98%</td>
<td>-0.09%</td>
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<tr>
<td></td>
<td>Disposal Flexibility</td>
<td>16.65%</td>
<td>=</td>
<td>16.43%</td>
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</tr>
<tr>
<td></td>
<td>Local Economic Development</td>
<td>14.40%</td>
<td>=</td>
<td>14.17%</td>
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<td>=</td>
<td>13.90%</td>
<td>-0.01%</td>
</tr>
<tr>
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<td>Increase Technical Workforce</td>
<td>13.15%</td>
<td>=</td>
<td>13.66%</td>
<td>+0.51%</td>
</tr>
<tr>
<td></td>
<td>Public &amp; Political Acceptance</td>
<td>11.59%</td>
<td>=</td>
<td>12.20%</td>
<td>+0.61%</td>
</tr>
<tr>
<td></td>
<td>Legal Resolution</td>
<td>11.22%</td>
<td>=</td>
<td>10.65%</td>
<td>-0.57%</td>
</tr>
<tr>
<td>Costs</td>
<td>Proliferation Prevention</td>
<td>26.39%</td>
<td>=</td>
<td>18.98%</td>
<td>-7.41%</td>
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<tr>
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<td>Facility Construction, Operation, &amp; Maintenance</td>
<td>18.18%</td>
<td>=</td>
<td>18.96%</td>
<td>+0.78%</td>
</tr>
<tr>
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<td>Supplemental Infrastructure Development</td>
<td>14.16%</td>
<td>=</td>
<td>14.83%</td>
<td>+0.67%</td>
</tr>
<tr>
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<td>Transportation</td>
<td>14.42%</td>
<td>=</td>
<td>14.14%</td>
<td>-0.28%</td>
</tr>
<tr>
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<td>Switching Policy</td>
<td>12.43%</td>
<td>=</td>
<td>12.91%</td>
<td>+0.48%</td>
</tr>
<tr>
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<td>Legal Fees &amp; Fines</td>
<td>11.29%</td>
<td>=</td>
<td>10.42%</td>
<td>-0.87%</td>
</tr>
<tr>
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<td>Licensing</td>
<td>10.36%</td>
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<td>9.75%</td>
<td>-0.61%</td>
</tr>
<tr>
<td>Opportunities</td>
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<td>=</td>
<td>25.32%</td>
<td>+3.32%</td>
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<tr>
<td></td>
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<td>19.12%</td>
<td>-0.36%</td>
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<td>+2</td>
<td>12.78%</td>
<td>-0.97%</td>
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<td>12.79%</td>
<td>=</td>
<td>12.69%</td>
<td>-0.10%</td>
</tr>
<tr>
<td></td>
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<td>12.28%</td>
<td>-2</td>
<td>12.44%</td>
<td>-0.16%</td>
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<tr>
<td>Risks</td>
<td>Accidents or Nuclear Material Release</td>
<td>24.09%</td>
<td>=</td>
<td>23.98%</td>
<td>-0.10%</td>
</tr>
<tr>
<td></td>
<td>Radiation Exposure</td>
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<td>=</td>
<td>23.72%</td>
<td>+0.17%</td>
</tr>
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<td>14.80%</td>
<td>=</td>
<td>14.57%</td>
<td>-0.23%</td>
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<tr>
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<td>Proliferation Potential</td>
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<td>11.98%</td>
<td>+0.21%</td>
</tr>
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<td>+0.66%</td>
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<td>7.83%</td>
<td>=</td>
<td>7.82%</td>
<td>-0.01%</td>
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</table>
Virginia Commonwealth University (VCU), led by Dr. Sama Bilbao y León, is working on a DOE NEUP project titled “Re-branding the nuclear fuel cycle”. The overall goal of the project is to develop an optimum path for the disposal of used nuclear fuel that takes into account both the technical challenges and the public’s perceptions. We respectfully request your help in comparing the relative importance of various criteria. The following is a list of some criteria important to the BENEFITS of a selected fuel cycle option. Please give us your opinion on which criterion is more important and by how much. If the criteria are of equal importance simply write equal. The reverse side has a brief description of each criterion. Two examples of comparing the preference are given first.

<table>
<thead>
<tr>
<th>Criterion A</th>
<th>Criterion B</th>
<th>Which one is more important?</th>
<th>How much more important?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dogs</td>
<td>Cats</td>
<td>A</td>
<td>X</td>
</tr>
<tr>
<td>Strawberry</td>
<td>Banana</td>
<td>Equal</td>
<td></td>
</tr>
<tr>
<td>Disposition Flexibility</td>
<td>Fuel Requirement Reduction</td>
<td></td>
<td></td>
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<tr>
<td>Disposition Flexibility</td>
<td>Infrastructure Development</td>
<td></td>
<td></td>
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<tr>
<td>Disposition Flexibility</td>
<td>Legal Resolution</td>
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<tr>
<td>Disposition Flexibility</td>
<td>Local Improvements</td>
<td></td>
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<tr>
<td>Disposition Flexibility</td>
<td>Nuclear Political Stability</td>
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<tr>
<td>Disposition Flexibility</td>
<td>Pollution &amp; Emissions Reduction</td>
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<tr>
<td>Fuel Requirement Reduction</td>
<td>Infrastructure Development</td>
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<td>Fuel Requirement Reduction</td>
<td>Legal Resolution</td>
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<td>Local Improvements</td>
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<td>Local Improvements</td>
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<td>Local Improvements</td>
<td>Pollution &amp; Emissions Reduction</td>
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</tr>
<tr>
<td>Nuclear Political Stability</td>
<td>Pollution &amp; Emissions Reduction</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Thank you for taking the time to complete this survey, if you would like to know more about this project or would like to be contacted further, please write your email address on this form or drop your business card off.

John Swanson
Graduate Research Assistant
Department of Mechanical & Nuclear Engineering
Virginia Commonwealth University
Email: swansonjm@vcu.edu
Explanation of 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.
Virginia Commonwealth University (VCU), led by Dr. Sama Bilbao y León, is working on a DOE NEUP project titled “Re-branding the nuclear fuel cycle”. The overall goal of the project is to develop an optimum path for the disposal of used nuclear fuel that takes into account both the technical challenges and the public’s perceptions. We respectfully request your help in comparing the relative importance of various criteria. The following is a list of some **criteria important to the COSTS of a selected fuel cycle option**. Please give us your opinion on which criterion is more important and by how much. If the criteria are of equal importance simply write *equal*. The reverse side has a brief description of each criterion. Two examples of comparing the preference are given first.

<table>
<thead>
<tr>
<th>Criterion A</th>
<th>Criterion B</th>
<th>Which one is more important?</th>
<th>How much more important?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dogs</td>
<td>Cats</td>
<td>A</td>
<td>X</td>
</tr>
<tr>
<td>Strawberry</td>
<td>Banana</td>
<td>Equal</td>
<td></td>
</tr>
<tr>
<td>Facility Construction &amp; Maintenance</td>
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<td>Facility Construction &amp; Maintenance</td>
<td>Transportation</td>
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<td>Legal Fees &amp; Fines</td>
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<td>Legal Fees &amp; Fines</td>
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<td>Licensing</td>
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<td>Transportation</td>
<td>Legal Fees &amp; Fines</td>
<td></td>
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</tr>
<tr>
<td>Transportation</td>
<td>Licensing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transportation</td>
<td>Proliferation Prevention</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transportation</td>
<td>Waste Amount</td>
<td></td>
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<tr>
<td>Legal Fees &amp; Fines</td>
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<td>Waste Amount</td>
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<td>Proliferation Prevention</td>
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<tr>
<td>Licensing</td>
<td>Waste Amount</td>
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</tr>
<tr>
<td>Proliferation Prevention</td>
<td>Waste Amount</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Thank you for taking the time to complete this survey, if you would like to know more about this project or would like to be contacted further, please write your email address on this form or drop your business card off.

John Swanson  
Graduate Research Assistant  
Department of Mechanical & Nuclear Engineering  
Virginia Commonwealth University  
Email: swansonjm@vcu.edu
Explanation of Criteria:

- **Facility Construction & Maintenance**
  - Cost associated with the construction and maintenance costs 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.
Virginia Commonwealth University (VCU), led by Dr. Sama Bilbao y León, is working on a DOE NEUP project titled “Re-branding the nuclear fuel cycle”. The overall goal of the project is to develop an optimum path for the disposal of used nuclear fuel that takes into account both the technical challenges and the public’s perceptions. We respectfully request your help in comparing the relative importance of various criteria. The following is a list of some criteria important to the OPPORTUNITIES of a selected fuel cycle option. Please give us your opinion on which criterion is more important and by how much. If the criteria are of equal importance simply write equal. The reverse side has a brief description of each criterion. Two examples of comparing the preference are given first.

<table>
<thead>
<tr>
<th>Criterion A</th>
<th>Criterion B</th>
<th>Which one is more important?</th>
<th>How much more important?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dogs</td>
<td>Cats</td>
<td>A</td>
<td>X</td>
</tr>
<tr>
<td>Strawberry</td>
<td>Banana</td>
<td>Equal</td>
<td></td>
</tr>
<tr>
<td>American Nuclear Development</td>
<td>Decommissioning Allowance</td>
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<td></td>
</tr>
<tr>
<td>American Nuclear Development</td>
<td>Energy Policy Leadership</td>
<td></td>
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</tr>
<tr>
<td>American Nuclear Development</td>
<td>Long-term Energy Security</td>
<td></td>
<td></td>
</tr>
<tr>
<td>American Nuclear Development</td>
<td>Promote Nuclear Industry</td>
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<td></td>
</tr>
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<td>American Nuclear Development</td>
<td>Technology Development</td>
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</tr>
<tr>
<td>American Nuclear Development</td>
<td>U.S. Government Competence</td>
<td></td>
<td></td>
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<tr>
<td>Decommissioning Allowance</td>
<td>Energy Policy Leadership</td>
<td></td>
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<td>Technology Development</td>
<td>U.S. Government Competence</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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John Swanson
Graduate Research Assistant
Department of Mechanical & Nuclear Engineering
Virginia Commonwealth University
Email: swansonjm@vcu.edu
Explanation of Criteria:

- **American Nuclear Development**
  - The opportunity of utilizing American resources, technology, labor 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.
Virginia Commonwealth University (VCU), led by Dr. Sama Bilbao y León, is working on a DOE NEUP project titled “Re-branding the nuclear fuel cycle”. The overall goal of the project is to develop an optimum path for the disposal of used nuclear fuel that takes into account both the technical challenges and the public’s perceptions. We respectfully request your help in comparing the relative importance of various criteria. The following is a list of some **criteria important to the RISKS of a selected fuel cycle option**. Please give us your opinion on which criterion is more important and by how much. If the criteria are of equal importance simply write *equal*. The reverse side has a brief description of each criterion. Two examples of comparing the preference are given first.

<table>
<thead>
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<th>Criterion A</th>
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</tr>
<tr>
<td>Strawberry</td>
<td>Banana</td>
<td>Equal</td>
<td></td>
</tr>
<tr>
<td>Feasibility</td>
<td>Potential Future Burden</td>
<td></td>
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<tr>
<td>Feasibility</td>
<td>Proliferation Potential</td>
<td></td>
<td></td>
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<tr>
<td>Feasibility</td>
<td>Public Perception</td>
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<tr>
<td>Feasibility</td>
<td>Radiotoxicity</td>
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<tr>
<td>Feasibility</td>
<td>Supply Availability</td>
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<tr>
<td>Feasibility</td>
<td>Waste Escape Accidents</td>
<td></td>
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</tr>
<tr>
<td>Potential Future Burden</td>
<td>Proliferation Potential</td>
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<tr>
<td>Potential Future Burden</td>
<td>Public Perception</td>
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<tr>
<td>Potential Future Burden</td>
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<td>Radiotoxicity</td>
<td>Supply Availability</td>
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<td>Waste Escape Accidents</td>
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<td>Supply Availability</td>
<td>Waste Escape Accidents</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Thank you for taking the time to complete this survey, if you would like to know more about this project or would like to be contacted further, please write your email address on this form or drop your business card off.

John Swanson  
Graduate Research Assistant  
Department of Mechanical & Nuclear Engineering  
Virginia Commonwealth University  
Email: swansonjm@vcu.edu
Explanation of 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 transuranics 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.
Appendix M

AHP SURVEY FOR SUBJECT MATTER EXPERTS
Virginia Commonwealth University (VCU) is working on a project sponsored by the US Department of Energy NEUP. Our objective is to choose the best method to dispose of used nuclear fuel in the long term.

The survey should take around 10 to 15 minutes to complete.

Thank you in advance for your help

Page 1 of 4
1. Please rank these groups from the most qualified (1) to the least qualified (5) in terms of selecting a method of used nuclear fuel disposal for the United States.

<table>
<thead>
<tr>
<th>Rank</th>
<th>Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Political Scientists: Experts in the social science that studies the policies and processes associated with the government of local, state, nation, and multinational institutions.</td>
</tr>
<tr>
<td>2</td>
<td>Nuclear Engineers &amp; Scientists: Experts in the branch of engineering that takes advantage of the atomic and nuclear properties of matter for the development of technologies and applications that benefit humankind (electricity, medical applications, industrial applications).</td>
</tr>
<tr>
<td>3</td>
<td>Economists: Experts in the study of how individuals and groups make decisions about how to utilize limited resources to best satisfy their wants, needs, and desires.</td>
</tr>
<tr>
<td>4</td>
<td>The General Public: Any concerned individual who is not necessarily a member of the other mentioned groups.</td>
</tr>
<tr>
<td>5</td>
<td>Environmental Scientists: Experts in the science that studies interactions between the physical, chemical, and biological components of the environment, including their effects on all types of organisms, but more often refers to human impact on the environment.</td>
</tr>
</tbody>
</table>
2. Finally, please compare each group against each other group with respect to who would be more qualified in selecting a method of used nuclear fuel disposal for the United States, and then by selecting how much more qualified that group is over the other group. If the groups are equally qualified, simply put equal. If equal, when asked "How much more qualified?" please select "N/A (choices are equal)".

As a reminder, the descriptions of the various groups are included below.

- **Economists**: Experts in the study of how individuals and groups make decisions about how to utilize limited resources to best satisfy their wants, needs, and desires.

- **Environmental Scientists**: Experts in the science that studies interactions between the physical, chemical, and biological components of the environment, including their effects on all types of organisms, but more often refers to human impact on the environment.

- **Nuclear Engineers & Scientists**: Experts in the branch of engineering that takes advantage of the atomic and nuclear properties of matter for the development of technologies and applications that benefit humankind (electricity, medical applications, industrial applications).

- **Political Scientists**: Experts in the social science that studies the policies and processes associated with the government of local, state, nation, and multinational institutions.

- **The General Public**: Any concerned individual who is not necessarily a member of the other mentioned groups.
3. Please indicate your current attitude toward using nuclear power as an energy source for the United States.

- [ ] Strongly Against
- [ ] Moderately Against
- [ ] Neutral
- [ ] Moderately Support
- [ ] Strongly Support

4. What is your gender?

5. What is your age?

6. What is the highest level of education you have completed?

7. What is your approximate average household income?

8. Which race/ethnicity best describes you? (Please choose only one.)

9. Where do you currently live?
Appendix N

MULTI-SCALE RATING SURVEY FOR SUBJECT MATTER EXPERTS
Virginia Commonwealth University (VCU) is working on a project pertaining to the public's perception of nuclear energy.

The survey comprises 7 questions and should take 10 minutes to complete.

Thank you in advance for your help.

Page 1 of 4

**1. Indicate YOUR PREFERENCES for following energy sources to generate electricity in the FUTURE.**

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Much less</th>
<th>Less</th>
<th>A little less</th>
<th>Same (no change)</th>
<th>A little more</th>
<th>More</th>
<th>Much more</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind</td>
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<tr>
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</tr>
<tr>
<td>Solar</td>
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</tr>
</tbody>
</table>

Page 2 of 4

**2. How qualified (credentials, competence, etc) are each of the following information sources for nuclear waste disposal information?**

<table>
<thead>
<tr>
<th>Information Source</th>
<th>Not Qualified at All</th>
<th>A Little Bit Qualified</th>
<th>Somewhat Qualified</th>
<th>Qualified</th>
<th>Very Qualified</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economists</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Environmental Scientists</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nuclear Engineers and Scientists</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Political Scientists</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The General Public</td>
<td></td>
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<td></td>
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<td></td>
</tr>
</tbody>
</table>

Page 211
**3. How honest (unbiased, trustworthy, etc) are each of the following information sources for nuclear waste disposal information?**

<table>
<thead>
<tr>
<th>Source</th>
<th>Not Honest at All</th>
<th>A Little Bit Honest</th>
<th>Somewhat Honest</th>
<th>Honest</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Economists</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Environmental Scientists</td>
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<td></td>
</tr>
<tr>
<td>The General Public</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

**4. How accessible (readily available and obtainable) is the information about nuclear waste disposal from each of the following sources?**

<table>
<thead>
<tr>
<th>Source</th>
<th>Not Accessible at All</th>
<th>A Little Bit Accessible</th>
<th>Somewhat Accessible</th>
<th>Accessible</th>
<th>Very Accessible</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economists</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Political Scientists</td>
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</tr>
<tr>
<td>The General Public</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**5. How understandable (easily understood by the general public) is the information about nuclear waste disposal from each of the following sources?**

<table>
<thead>
<tr>
<th>Source</th>
<th>Not Understandable at All</th>
<th>A Little Bit Understandable</th>
<th>Somewhat Understandable</th>
<th>Understandable</th>
<th>Very Understandable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economists</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>The General Public</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
6. Which race/ethnicity best describes you? (Please choose only one.)

- American Indian or Alaskan Native
- Asian / Pacific Islander
- Black or African American
- Hispanic American
- White / Caucasian
- From multiple races
- Other

7. Please share any additional thoughts you may have about nuclear energy or energy sources in general.

Thank you for taking the time to complete this survey.
Appendix O

AHP SURVEY FOR BENEFITS OBJECTIVES
Virginia Commonwealth University (VCU) is working on a project sponsored by the US Department of Energy NEUP. Our objective is to choose the best method to dispose of used nuclear fuel in the long term.

The survey should take around 10 to 15 minutes to complete.

Thank you in advance for your help.

---

1. 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.

<table>
<thead>
<tr>
<th>Rank</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Disposal Flexibility: 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.</td>
</tr>
<tr>
<td>2</td>
<td>Local Economic Development: 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.).</td>
</tr>
<tr>
<td>3</td>
<td>Legal Resolution: 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.</td>
</tr>
<tr>
<td>4</td>
<td>Fuel Requirement Reduction: The benefits of selecting a fuel cycle that reduces the need to mine or import additional nuclear fuel (i.e. uranium).</td>
</tr>
<tr>
<td>5</td>
<td>National Infrastructure Development: The benefits gained from the development of national infrastructure (i.e. interstate highways, railways, and support facilities) in connection with a selected fuel cycle.</td>
</tr>
<tr>
<td>6</td>
<td>Public &amp; 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.</td>
</tr>
<tr>
<td>7</td>
<td>Increase Technical Workforce: The benefits of choosing a fuel cycle that promotes the training of more high-paid engineers, scientists, and technical professionals.</td>
</tr>
</tbody>
</table>
2. Please select which criterion is more important in terms of the BENEFITS that can be derived from the selection of a method for the disposal of used nuclear fuel in the US, and then please select by how much. If the criteria are equally qualified, simply put equal. If equal, when asked "How much more important?" please select "N/A (choices are equal)". As a reminder, the descriptions of the various criteria are included below.

<table>
<thead>
<tr>
<th>Which one is more important?</th>
<th>How much more important?</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A) Disposal Flexibility</td>
<td>(B) Public &amp; Political Acceptance</td>
</tr>
<tr>
<td>(A) National Infrastructure Development</td>
<td>(B) Increase Technical Workforce</td>
</tr>
<tr>
<td>(A) Fuel Requirement Reduction</td>
<td>(B) Public &amp; Political Acceptance</td>
</tr>
<tr>
<td>(A) National Infrastructure Development</td>
<td>(B) Local Economic Development</td>
</tr>
<tr>
<td>(A) Public &amp; Political Acceptance</td>
<td>(B) Increase Technical Workforce</td>
</tr>
<tr>
<td>(A) Disposal Flexibility</td>
<td>(B) Legal Resolution</td>
</tr>
<tr>
<td>(A) Disposal Flexibility</td>
<td>(B) National Infrastructure Development</td>
</tr>
<tr>
<td>(A) Fuel Requirement Reduction</td>
<td>(B) Increase Technical Workforce</td>
</tr>
<tr>
<td>(A) Disposal Flexibility</td>
<td>(B) Local Economic Development</td>
</tr>
<tr>
<td>(A) Fuel Requirement Reduction</td>
<td>(B) Local Economic Development</td>
</tr>
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<td>(B) Local Economic Development</td>
</tr>
<tr>
<td>(A) Fuel Requirement Reduction</td>
<td>(B) National Infrastructure Development</td>
</tr>
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<td>(B) Increase Technical Workforce</td>
</tr>
<tr>
<td>(A) National Infrastructure Development</td>
<td>(B) Legal Resolution</td>
</tr>
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<td>(A) Legal Resolution</td>
<td>(B) Public &amp; Political Acceptance</td>
</tr>
<tr>
<td>(A) Local Economic Development</td>
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<td>(B) Increase Technical Workforce</td>
</tr>
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<td>(A) Disposal Flexibility</td>
<td>(B) Increase Technical Workforce</td>
</tr>
<tr>
<td>(A) Fuel Requirement Reduction</td>
<td>(B) Legal Resolution</td>
</tr>
<tr>
<td>(A) Disposal Flexibility</td>
<td>(B) Fuel Requirement Reduction</td>
</tr>
</tbody>
</table>
Explanation of BENEFITS criteria important for selecting a method of used nuclear fuel disposal, also known as a nuclear fuel cycle:

Disposal Flexibility
- 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.

Fuel Requirement Reduction
- The benefits of selecting a fuel cycle that reduces the need to mine or import additional nuclear fuel (i.e. uranium).

National Infrastructure Development
- The benefits gained from the development of national infrastructure (i.e. interstate highways, railways, and support facilities) in connection with a selected fuel cycle.

Legal Resolution
- 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.

Local Economic Development
- 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.).

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.

Increase Technical Workforce
- The benefits of choosing a fuel cycle that promotes the training of more high-paid engineers, scientists, and technical professionals.

3. Please indicate your current attitude toward using nuclear power as an energy source for the United States.

- [ ] Strongly Against
- [ ] Moderately Against
- [ ] Neutral
- [ ] Moderately Support
- [ ] Strongly Support

4. What is your gender?

5. What is your age?

6. What is the highest level of education you have completed?

7. What is your approximate average household income?
8. Which race/ethnicity best describes you? (Please choose only one.)

9. Where do you currently live?

Thank you for taking the time to complete this survey.

Page 4 of 4
Virginia Commonwealth University (VCU) is working on a project sponsored by the US Department of Energy NEUP. Our objective is to choose the best method to dispose of used nuclear fuel in the long term.

The survey should take around 10 to 15 minutes to complete.

Thank you in advance for your help

---

**1. Please rank the following criteria from the most important (1) to the least important (7) in terms of the COSTS that are developed from the selection of a given method for the disposal of used nuclear fuel in the US.**

<table>
<thead>
<tr>
<th>Rank</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Transportation: The costs of the transportation of the used fuel in a selected fuel cycle (trucks, drivers, barges, trains, etc.)</td>
</tr>
<tr>
<td>2</td>
<td>Proliferation Prevention: 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).</td>
</tr>
<tr>
<td>3</td>
<td>Facility Construction, Operation, &amp; Maintenance: The costs associated with the construction, operation and maintenance of any required facility (repository, reprocessing facility, etc.) for a selected fuel cycle.</td>
</tr>
<tr>
<td>4</td>
<td>Switching Policy: The costs of switching from the currently selected fuel cycle to an alternative fuel cycle (i.e. workforce retooling, legislation, sunk costs).</td>
</tr>
<tr>
<td>5</td>
<td>Legal Fees &amp; Fines: 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.</td>
</tr>
<tr>
<td>6</td>
<td>Supplemental Infrastructure Development: The costs of developing the additional infrastructure (i.e. interstate highways, railways, and technical workforce) required for a selected fuel cycle.</td>
</tr>
<tr>
<td>7</td>
<td>Licensing: The costs associated with the licensing of facilities, related technologies, and methods for a selected fuel cycle.</td>
</tr>
</tbody>
</table>
2. Please select which criterion is more important in terms of the COSTS that are developed from the selection of a method for the disposal of used nuclear fuel in the US, and then please select by how much. If the criteria are equally qualified, simply put equal. If equal, when asked "How much more important?" please select "N/A (choices are equal)". As a reminder, the descriptions of the various criteria are included below.

<table>
<thead>
<tr>
<th>Criterion 1</th>
<th>Criterion 2</th>
<th>Which one is more important?</th>
<th>How much more important?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supplemental Infrastructure Development</td>
<td>Switching Policy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Licensing</td>
<td>Supplemental Infrastructure Development</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Facility Construction, Operation, &amp; Maintenance</td>
<td>Legal Fees &amp; Fines</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Legal Fees &amp; Fines</td>
<td>Supplemental Infrastructure Development</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proliferation Potential</td>
<td>Switching Policy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Switching Policy</td>
<td>Transportation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proliferation Potential</td>
<td>Supplemental Infrastructure Development</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Licensing</td>
<td>Proliferation Potential</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supplemental Infrastructure Development</td>
<td>Transportation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Licensing</td>
<td>Switching Policy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Licensing</td>
<td>Transportation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Facility Construction, Operation, &amp; Maintenance</td>
<td>Switching Policy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Legal Fees &amp; Fines</td>
<td>Proliferation Potential</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Facility Construction, Operation, &amp; Maintenance</td>
<td>Proliferation Potential</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Legal Fees &amp; Fines</td>
<td>Transportation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Facility Construction, Operation, &amp; Maintenance</td>
<td>Licensing</td>
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</tr>
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<td>Supplemental Infrastructure Development</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Legal Fees &amp; Fines</td>
<td>Licensing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proliferation Potential</td>
<td>Transportation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Legal Fees &amp; Fines</td>
<td>Switching Policy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Facility Construction, Operation, &amp; Maintenance</td>
<td>Transportation</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Explanation of COSTS criteria important for selecting a method of used nuclear fuel disposal, i.e. the nuclear fuel cycle:

Facility Construction, Operation, & Maintenance
• The costs associated with the construction, operation and maintenance of any required facility (repository, reprocessing facility, etc.) for a selected fuel cycle.

Legal Fees & Fines
• 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.

Licensing
• The costs associated with the licensing of facilities, related technologies, and methods for a selected fuel cycle.

Proliferation Prevention
• 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).

Supplemental Infrastructure Development
• The costs of developing the additional infrastructure (i.e. interstate highways, railways, and technical workforce) required for a selected fuel cycle.

Switching Policy
• The costs of switching from the currently selected fuel cycle to an alternative fuel cycle (i.e. workforce retooling, legislation, sunk costs).

Transportation
• The costs of the transportation of the used fuel in a selected fuel cycle (trucks, drivers, barges, trains, etc.)

*3. Please indicate your current attitude toward using nuclear power as an energy source for the United States.

☐ Strongly Against ☐ Moderately Against ☐ Neutral ☐ Moderately Support ☐ Strongly Support

*4. What is your gender?

☐ Male ☐ Female

*5. What is your age?

☐ 20-29 ☐ 30-39 ☐ 40-49 ☐ 50-59 ☐ 60-69 ☐ 70 or older

*6. What is the highest level of education you have completed?

☐ High School Diploma ☐ Some College ☐ Associate's Degree ☐ Bachelor's Degree ☐ Master's Degree ☐ Doctorate

*7. What is your approximate average household income?

☐ Under $30,000 ☐ $30,000 - $50,000 ☐ $50,000 - $75,000 ☐ $75,000 - $100,000 ☐ $100,000 - $150,000 ☐ Over $150,000

8. Which race/ethnicity best describes you? (Please choose only one.)

☐ African American/Civilian ☐ Asian ☐ Native American/Alaskan Native ☐ Hispanic/Latino ☐ Other ☐ White/Caucasian
9. Where do you currently live?

Thank you for taking the time to complete this survey.

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Appendix Q

AHP SURVEY FOR OPPORTUNITIES OBJECTIVES
1. Please rank the following criteria from the most important (1) to the least important (6) in terms of the OPPORTUNITIES that can be derived from the selection of a given method for the disposal of used nuclear fuel in the US.

<table>
<thead>
<tr>
<th>Rank</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>American Economic Development: The opportunity of selecting a fuel cycle that stimulates the national economy due to job creation and tax revenue.</td>
</tr>
<tr>
<td>6</td>
<td>Energy Policy Leadership: 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.</td>
</tr>
<tr>
<td>6</td>
<td>Nuclear Industry Growth: 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.</td>
</tr>
<tr>
<td>6</td>
<td>Long-term Electricity Production: 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.</td>
</tr>
<tr>
<td>6</td>
<td>New Technology Development: 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.</td>
</tr>
<tr>
<td>6</td>
<td>U.S. Government Competence: 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.</td>
</tr>
</tbody>
</table>
2. Please select which criterion is more important in terms of the OPPORTUNITIES that
   can be derived from the selection of a method for the disposal of used nuclear fuel in the
   US, and then please select by how much. If the criteria are equally qualified, simply put
   equal. If equal, when asked "How much more important?" please select "N/A (choices are
equal)".

As a reminder, the descriptions of the various criteria are included below.

<table>
<thead>
<tr>
<th>(A) American Economic Development</th>
<th>(B) Nuclear Industry Growth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Which one is more important?</td>
</tr>
<tr>
<td></td>
<td>How much more important?</td>
</tr>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(A) Energy Policy Leadership</th>
<th>(B) U.S. Government Competence</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A) American Economic Development</td>
<td>(B) Energy Policy Leadership</td>
</tr>
<tr>
<td>(A) American Economic Development</td>
<td>(B) U.S. Government Competence</td>
</tr>
<tr>
<td>(A) American Economic Development</td>
<td>(B) Long-term Electricity Production</td>
</tr>
<tr>
<td>(A) New Technology Development</td>
<td>(B) Nuclear Industry Growth</td>
</tr>
<tr>
<td>(A) American Economic Development</td>
<td>(B) New Technology Development</td>
</tr>
<tr>
<td>(A) Energy Policy Leadership</td>
<td>(B) Long-term Electricity Production</td>
</tr>
<tr>
<td>(A) Long-term Electricity Production</td>
<td>(B) New Technology Development</td>
</tr>
<tr>
<td>(A) Long-term Electricity Production</td>
<td>(B) Nuclear Industry Growth</td>
</tr>
<tr>
<td>(A) Energy Policy Leadership</td>
<td>(B) New Technology Development</td>
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<td>(A) Energy Policy Leadership</td>
<td>(B) Nuclear Industry Growth</td>
</tr>
<tr>
<td>(A) New Technology Development</td>
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<tr>
<td>(A) Long-term Electricity Production</td>
<td>(B) U.S. Government Competence</td>
</tr>
<tr>
<td>(A) Nuclear Industry Growth</td>
<td>(B) Energy Policy Leadership</td>
</tr>
</tbody>
</table>

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Explanation of OPPORTUNITIES Criteria:

American Economic Development
• The opportunity of selecting a fuel cycle that stimulates the national economy due to job creation and tax revenue.

Energy Policy Leadership
• 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.

Long-term Electricity Production
• 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.

New Technology Development
• 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.

Nuclear Industry Growth
• 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.

U.S. Government Competence
• 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.

* 3. Please indicate your current attitude toward using nuclear power as an energy source for the United States.

☐ Strongly Against  ☐ Moderately Against  ☐ Neutral  ☐ Moderately Support  ☐ Strongly Support

* 4. What is your gender?

☐

* 5. What is your age?

☐

* 6. What is the highest level of education you have completed?

☐

* 7. What is your approximate average household income?

☐
8. Which race/ethnicity best describes you? (Please choose only one)

- Other (please specify) 

9. Where do you currently live?

- 

Thank you for taking the time to complete this survey.
Appendix R

AHP SURVEY FOR RISKS OBJECTIVES
Virginia Commonwealth University (VCU) is working on a project sponsored by the US Department of Energy NEUP. Our objective is to choose the best method to dispose of used nuclear fuel in the long term.

The survey should take around 10 to 15 minutes to complete.

Thank you in advance for your help.

Page 1 of 4

*1. Please rank the following criteria from the most important (1) to the least important (7) in terms of the RISKS that may be developed from the selection of a given method for the disposal of used nuclear fuel in the US.

- Supply Availability: The risk of the fuel inventory being consumed faster than it can be replenished as a result of a selected fuel cycle.
- Potential Future Burden: 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.
- Public or Political Rejection: The risk of not having the majority agree that a selected fuel cycle satisfies the needs of society or provides “peace of mind” to either policy makers or the general public.
- Proliferation Potential: The risk of selecting a fuel cycle that has greater potential of having nuclear materials diverted for non-authorized applications (i.e. weapons).
- Radiation Exposure: The risk of site-workers and the general public being exposed to radiation generated by the used nuclear fuel due to a selected fuel cycle.
- Accidents or Nuclear Material Release: 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.
- Technical Feasibility: The risk associated with choosing a fuel cycle that requires technology that has not yet been developed, thus preventing a fuel cycle’s implementation immediately or in the near-future.

Page 2 of 4
Please select which criterion is more important in terms of the RISKS that are developed from the selection of a method for the disposal of waste in the US, and then please select by how much. If the criteria are equally qualified, simply put equal. If equal, when asked "How much more important?" please select "N/A (choices are equal)". As a reminder, the descriptions of the various criteria are included below.

<table>
<thead>
<tr>
<th>(A) Accidents or Nuclear Material Release — (B) Supply Availability</th>
<th>Which one is more important?</th>
<th>How much more important?</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A) Supply Availability ———— (B) Technical Feasibility</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(A) Radiation Exposure ———— (B) Technical Feasibility</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(A) Accidents or Nuclear Material Release — (B) Proliferation Potential</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(A) Proliferation Potential ——— (B) Radiation Exposure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(A) Public or Political Rejection ——— (B) Technical Feasibility</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(A) Accidents or Nuclear Material Release — (B) Potential Future Burden</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(A) Potential Future Burden ——— (B) Supply Availability</td>
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<td></td>
</tr>
<tr>
<td>(A) Accidents or Nuclear Material Release — (B) Technical Feasibility</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(A) Proliferation Potential ——— (B) Supply Availability</td>
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<td></td>
</tr>
<tr>
<td>(A) Proliferation Potential ——— (B) Technical Feasibility</td>
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<tr>
<td>(A) Potential Future Burden ——— (B) Radiation Exposure</td>
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<tr>
<td>(A) Accidents or Nuclear Material Release — (B) Radiation Exposure</td>
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<tr>
<td>(A) Radiation Exposure ——— (B) Supply Availability</td>
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<tr>
<td>(A) Accidents or Nuclear Material Release — (B) Public or Political Rejection</td>
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<tr>
<td>(A) Public or Political Rejection ——— (B) Radiation Exposure</td>
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<td>(A) Potential Future Burden ——— (B) Technical Feasibility</td>
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<td>(A) Potential Future Burden ——— (B) Proliferation Potential</td>
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<tr>
<td>(A) Proliferation Potential ——— (B) Public or Political Rejection</td>
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<td></td>
</tr>
<tr>
<td>(A) Public or Political Rejection ——— (B) Supply Availability</td>
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<td></td>
</tr>
<tr>
<td>(A) Potential Future Burden ——— (B) Public or Political Rejection</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Explanation of RISKS Criteria important for selecting a method of used nuclear fuel disposal, i.e. the nuclear fuel cycle:

Accidents or Nuclear Material Release:
• 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.

Potential Future Burden
• 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.

Proliferation Potential
• The risk of selecting a fuel cycle that has greater potential of having nuclear materials diverted for non-authorized applications (i.e. weapons).

Public or Political Rejection:
• The risk 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.

Radiation Exposure
• 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.

Supply Availability
• The risk of the fuel inventory being consumed faster than it can be replenished as a result of the selected fuel cycle.

Technical Feasibility
• 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.

3. What is your gender?

4. What is your age?

5. What is the highest level of education you have completed?

6. What is your approximate average household income?

7. Which race/ethnicity best describes you? (Please choose only one)

8. Where do you currently live?
Thank you for taking the time to complete this survey.
REFERENCES


John Michael Swanson was born on July 1, 1991, in Tampa, Florida, and is a citizen of the United States of America. He graduated from Midlothian High School in Midlothian, Virginia in 2009. He received his Bachelor of Science in Mechanical Engineering from Virginia Commonwealth University in 2013, graduating *Summa Cum Laude*. He performed three internships, one at Stryker in Kiel, Germany testing biomedical devices in 2012, one at Virginia Commonwealth University in Richmond, Virginia researching mechanical ventilation from 2012 to 2013, and one at Intellibot Robotics in Richmond, Virginia designing and testing robots in 2013. He passed the Fundamentals of Engineering exam in 2013. His senior design team won Best Mechanical Engineering Project at the VCU Senior Design Expo 2013. He has published one journal article in collaboration with Dr. Ramana Pidaparti at the University of Georgia for their work on mechanical ventilation in the *Journal of Medical Engineering & Technology* in January 2015. Additionally, he has published four conference papers in total, one at each of the following: the ANS Student Conference 2014, the ANS Winter Meeting 2014, the Waste Management Conference 2015, and the ANS International High-Level Radioactive Waste Management Conference 2015.