An Analytic-Deliberative Process for the Selection and Deployment of Radiation Detection Systems for Shipping Ports and Border Crossings

By

Michael B. Shattan

B.S. Mechanical Engineering
United States Military Academy, 1999

Submitted to the Department of Nuclear Science and Engineering in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Nuclear Engineering

At the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
May 2008

Signature of Author ______________________________
Department of Nuclear Science and Engineering
May 9, 2008

Certified by ______________________________
George E. Apostolakis – Thesis Supervisor
Professor of Nuclear Science and Engineering
Professor of Engineering Systems

Certified by ______________________________
Dwight L. Williams – Thesis Reader
Visiting Professor of Nuclear Science and Engineering
Department of Defense Chief Engineer and Principal Nuclear Physicist

Accepted by ______________________________
Professor Jacquelyn Yanch
Chair, Department Committee on Graduate Students

An Analytic-Deliberative Process for the Selection and Deployment of Radiation Detection Systems for Shipping Ports and Border Crossings

by

Michael B. Shattan

Submitted to the Department of Nuclear Science and Engineering on May 9, 2008 in Partial Fulfillment of the Requirements for the Degree of Master of Science in Nuclear Engineering

ABSTRACT

Combating the threat of nuclear smuggling through shipping ports and border crossings has been recognized as a national priority in defending the US against nuclear terrorism. In light of the SAFE Port act of 2006, the Domestic Nuclear Detection Office (DNDO) has been charged with the responsibility of providing the Customs and Border Protection Agency (CBP) with the capability to conduct 100% radiological screening of all containers entering the country. In an attempt to meet this mandate, the DNDO has conducted a typical government acquisition procedure to develop and acquire radiation portal monitors (RPMs) capable of passive gamma-ray spectroscopy that would allow 100% radiological screening without detrimental affects on the stream of commerce through the terminals. However, the Cost-Benefit Analysis (CBA) supporting the DNDO decision-making process has been criticised and has delayed the program significantly.

We propose an Analytic-Deliberative Process (ADP) as an alternative to CBA for this application. We conduct a case study with four DNDO stakeholders using the ADP proposed by the National Research Council in the context of environmental remediation and adapted by the MIT group and compare the results to those derived from DNDO's CBA. The process involves value modeling using an objectives hierarchy and the analytic hierarchy process. Value functions are derived and expected outcomes for the decision options are elicited from the stakeholders. The process results in a preference ranking of the decision options in order of value to each stakeholder. The analytical results are then used to structure a deliberation in which the four stakeholders use both the analytical results and any pertinent information outside the analysis to form a consensus.

The final decision of both the CBA and ADP models show good agreement and demonstrate the validity of both methods. However, the ADP format is better at explicitly capturing and quantifying subjective influences affecting the final decision. This facilitates discussion and leads to faster consensus building.

Thesis Supervisor: George E. Apostolakis
Title: Professor of Nuclear Engineering
Professor of Engineering Systems

(This page intentionally left blank)

Acknowledgements

I would like to thank my advisor, Professor George Apostolakis, for his guidance, advice and support. I would also like to thank my reader, Dr. Dwight Williams, whose insightful comments have added much to my final product. Many thanks are also due to Michael Stawicki who spent innumerable selfless hours sharing his insights with me on the ADP and life as a graduate student.

This work would not have been possible without the unwavering support of LTC Nicholas Prins and Mr. Julian Hill of the Domestic Nuclear Detection Office. Their willing participation, insights and leadership were paramount to the successful completion of this work. I would also like to offer my gratitude to Todd Pardue, Ernie Muencha of the Domestic Nuclear Detection Office and Patrick Simmons of the Customs and Border Protection Agency each of whom to the time to provide me with critical insights and information. The views expressed presented here are those of the author and do not necessarily represent the views of DNDO.

I would like to thank my family who always believed I could accomplish more than I thought I could. My mother and father have been a bedrock of moral encouragement and inspiration. I would like to thank my son Dustin, who never fails to remind me of what is important in life, and never fails to raise my spirits with his smiles and hugs. And finally my deepest thanks are for my wife, Melanie. Her unwavering support of my ambitions and self sacrifices truly humble me. She is the foundation upon which everything good in my life stands.

(This page intentionally left blank)

Table of Contents

(This page intentionally left blank)

List of Figures

(This page intentionally left blank)

List of Tables

(This page intentionally left blank)

Nomenclature

ADP	Analytic Deliberative Process
AHP	Analytic Hierarchy Process
CBA	Cost-Benefit Analysis
CBP	Customs and Border Protection Agency
DA	Decision Analysis
DNDO	Domestic Nuclear Detection Office
DTRA	Defense Threat Reduction Agency
DUT	Discounted Utility Theory
FWHM	Full Width Half Maximum
GAO	Government Accountability Office
HPGe	High Purity Germanium
MCS	Mortality Cost Savings
MIT	Massachusetts Institute of Technology
NaI	Sodium-Iodide
NORM	Naturally Occurring Radiation
PI	Performance Index
PVT	Poly-Vinyl Toluene
RIID	Radio-Isotope Identification Device
RPM	Radiation Portal Monitor
SNM	Special Nuclear Materials
TEU	Twenty Foot Equivalent Units
US EPA	United States of America Environmental Protection Agency

VSL	Value of a Statistical Life
WTA	Willingness to Accept
WTP	Willingness to Pay

(This page intentionally left blank)

1. INTRODUCTION

The Domestic Nuclear Detection Office (DNDO) is a jointly-staffed national office established to develop a global nuclear detection architecture, to acquire and support the deployment of domestic detection systems, and to detect and report attempts to import or transport a nuclear device or fissile or radiological material intended for illicit use. One critical DNDO objective is to provide effective systems for radiological screening at America's shipping ports and border crossings which it currently does with simple plastic scintillators. Although these systems succeed in providing a high sensitivity to radiation they have been considered inadequate because of their negative impact on the flow of commerce due to high false positive (nuisance alarm) rates and a poor ability to identify illicit radiological materials in cargo with naturally occurring radiation (NORM).

In September of 2005, DNDO sought to remedy this deficiency by initiating a solicitation process for new detection systems that use passive gamma-ray spectroscopy to replace the outdated systems. In attempting to decide between different system designs and deployment options, DNDO has performed a cost-benefit analysis (CBA) that includes value judgments on the relative importance of the goals of the program such as minimizing cost, maximizing detection capability, and minimizing the impact on stream of commerce among others.

The results of the CBA have been questioned (Aloise, 2007) because several critical inputs to the analysis are very difficult to quantify in terms of dollars and require broad assumptions. Previous work by Bier (Bier, 2005) and Keeney (Keeney, 2007) describe the difficulties in quantifying the probability and location of a possible terrorist attack and suggest a game theory based approach to find a solution. Smith and Hallstrom (Smith and Hallstrom, 2004) have proposed a benefit-cost model for the Department of Homeland Security policies that advocates using stated and revealed preferences to estimate the consequences of terrorist attacks. Paté-Cornell and Guikema advocate using approaches similar to the above references for quantifying the full spectrum of terrorism risks and prioritizing countermeasures. (Paté-Cornell and Guikema, 2002).

The uncertainties associated with these dollar figures must be necessarily large, especially when considering the possibility of a nuclear device detonation. Additional complications arise from the input of stakeholders. The Custom and Border Protection Agency (CBP), the end user, holds significant influence over the final DNDO decision. Political influences will undoubtedly play some role as well. Although agencies such as DNDO strive to make these types of decisions as objectively as possible, subjective evaluations are unavoidable both in the decision maker's preferences to establish disaster consequence levels within the rigorous analysis, and in eliciting the opinions of stakeholders outside the analysis.

The objective of this paper is to propose the use of the analytic-deliberative process (ADP) as an alternative to CBA for selecting and deploying radiation portal monitors (RPM's) at shipping ports and border crossings. This process has been proposed by the National Research Council (National Research Council, 1996) in the context of environmental decision making. It has been applied by the MIT group to a number of situations (Weil and Apostolakis, 2001) including terrorism (Koonce and Apostolakis, 2008). Our approach is similar to the systems approach for prioritizing terrorism countermeasures suggested Paté-Cornell and Guikema (Paté-Cornell and Guikema, 2002) but is tailored to the specific application of DNDO's RPM acquisition decision and explicitly treats the subjective influences outside of a systems analysis that inevitably affect these kinds of decisions. The ADP may streamline the decision making process by providing an explicit method by which stakeholders use analytical tools to shape their deliberation by explicitly and separately analyzing their subjective values and objective system performance data resulting in a better understanding of their differences. The ADP provides the stakeholders with insights that may be helpful in reaching a consensus. We also report on an actual deliberation held by DNDO decision makers using this process and compare the results to that of a CBA based deliberation held earlier for the same decision.

Section 2 discusses an overview of the ADP and how it is implemented in this problem. Section 3 describes the case study, decision options considered by DNDO, and addresses their strengths and weaknesses. Section 4 discusses the results of the analysis and the insights it provided. Section 5 describes the actual deliberation and provides the final results. Section 6 summarizes our conclusions. Appendix A provides a technical and practical comparison of the two main types of radiation detectors used in forming the decision options. Appendix B discusses the influences of Naturally Occurring Radioactive Material (NORM) on the performance of RPMs. Appendix D provides a background on how CBA is used today in public policy decision making and Appendix E provides a brief comparison of the strengths and weakness of CBA and traditional Decision Analysis (DA) techniques for public policy decision making.

2. METHODOLOGY – THE ANALYTIC/DELIBERATIVE PROCESS

The ADP methodology (National Research Council, 1996) consists of two major parts:

1. "*Analysis* refers to ways of building understanding by systematically applying specific theories and methods that have been developed within communities of expertise, such as those of the natural science, social science, engineering, decision science, logic, mathematics and law."
2. "*Deliberation* is any formal or informal process for communication and collective consideration of issues."

In our work, ADP is conducted in five steps and is illustrated in Figure 1 (details will be provided later). The first step captures all the objectives of stakeholders by constructing an objectives hierarchy or value tree. The objectives hierarchy used by DNDO in this project consists of the tiers labeled *goal, impact categories*, and *objectives* in Figure 1. In this step, the objectives are also weighted by importance to the achievement of the overall goal from the perspective of the decision maker. In addition, value functions are developed for each objective. The second step of the ADP involves formulating a complete set of feasible decision options that the decision makers will consider. In the third step of the ADP, the analyst analyzes the decision options to determine how well they achieve each objective and ranks the decision options from best to worst based on the decision maker's priorities. The fourth step of the ADP is the deliberation. During the deliberation, all stakeholders involved in the decision-making process meet to review the analytical results and consider both the objective and subjective influences that have led to the final rankings. Influences on the decision problem that were not appropriate for the formal analysis are typically discussed in this step. The stakeholders then use the insights from the analysis to build a consensus that may or may not agree with the results of the analysis. The fifth step of the ADP is to track, update, and adjust the decision as necessary through the implementation stage. Since new information and insights may continue to be revealed after the decision is made, it is important for both the stakeholders and the analyst to remain vigilant through the implementation phase.

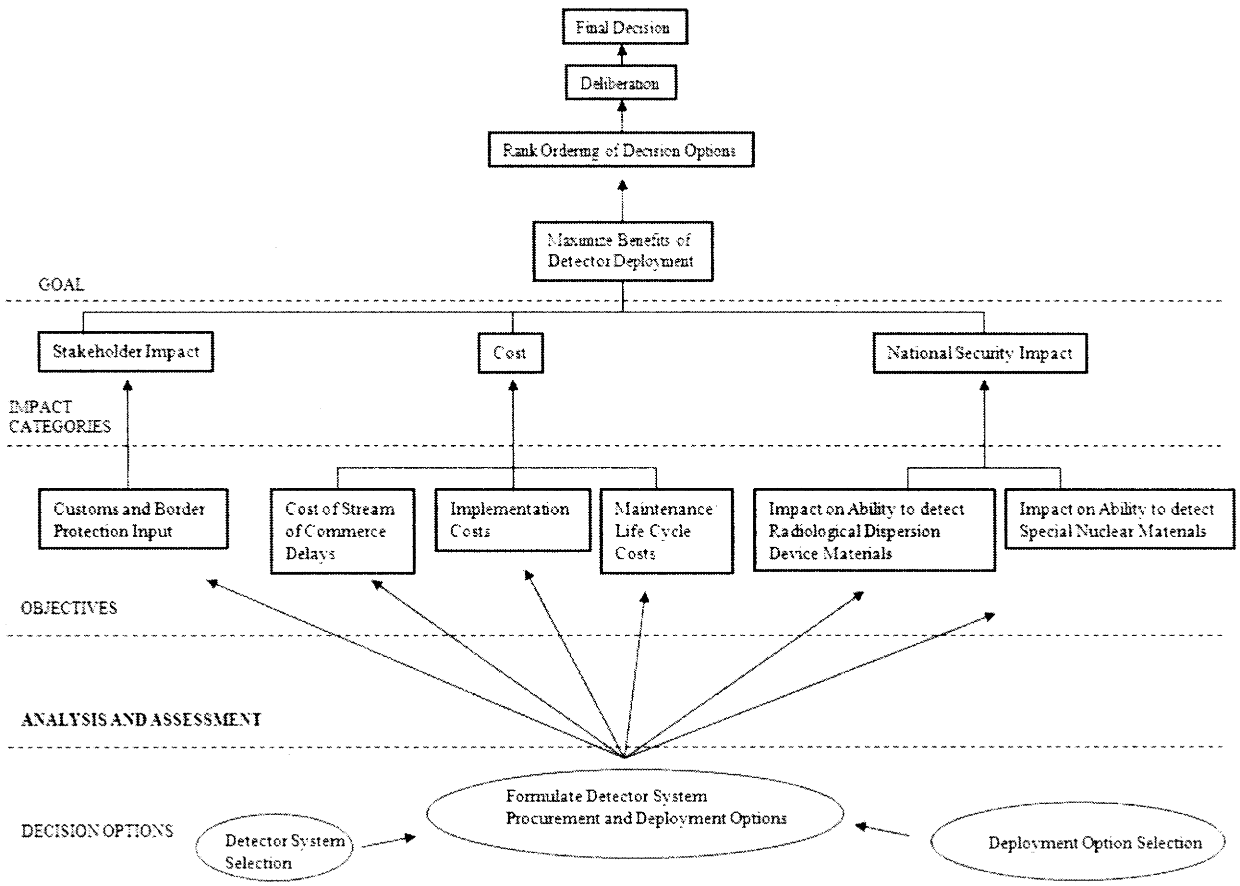

Figure 1: The Analytic-Deliberative Process

2.1 Defining the Objectives

2.1.1 Building an Objectives Hierarchy

Building an objectives hierarchy allows the decision makers to focus on what they are trying to achieve. The objectives structure places broad, fundamental objectives at the top of the tree and illustrates how achieving each sub-objective contributes to achieving the overall goal. The objectives hierarchy used by DNDO in this project is shown as the middle portion of Figure 1. The procedure begins by working with the stakeholders to define what the overall goal is that they are trying to achieve. In this case: *Maximize the Benefits of Detector Deployment*. With the overall goal in mind, the stakeholders then define the categories of fundamental objectives that need to be satisfied in order to achieve the overall goal. These are the impact categories in Fig. 1. In this case study, three impact categories were defined: *Impact on Stakeholders, Impact on Cost, and Impact on National Security.* Fundamental objectives are then defined that explain what we are trying to achieve in each impact category. These fundamental objectives are a set of objectives that are complete, as few as possible, and not redundant (Clemen, 1996, 533-534). They are also quantifiable, as explained in the next section.

2.1.2 Developing Constructed Scales

A critical step in defining the objectives is to develop a set of constructed scales by which to measure how well the decision options meet these objectives. The capabilities of the systems can be mapped onto the constructed scales for which we can derive a value function. The constructed scales are generally, but not always, represented by a set of discrete levels chosen by the stakeholders to help them differentiate between the impacts of the different decision options. For example, for the objective *Ability to detect Special Nuclear Materials (SNM)* the false negative rate (probability of SNM slipping through) describes how well a decision option might meet this objective. A constructed scale for this objective might look like that in Table 1. The scale is bounded by worst and best cases for conceivable false negative rates. It includes four levels chosen by the stakeholders to indicate different capability levels that have different values to them. The mapping of the performance measure false negative rate to the constructed scale is displayed adjacent to each level.

Table 1: A Constructed Scale

Ability to detect SNM	
Level	Expected False Negative Rate
Excellent	<2%
Good	2-10%
Fair	10-20%
Bad	>20%

Deliberation between the stakeholders on what the objectives hierarchy should be is critical to ensuring that the analysis provides meaningful results. A consensus among stakeholders on the objectives hierarchy and constructed scales would be desirable before moving forward. However, if this is not achievable, separate analyses would be carried out for the stakeholders postponing the attempt at consensus to the final deliberation (Apostolakis and Pickett, 1998).

2.1.3 Weighting the Objectives

Once the objectives are completely defined with their constructed scales, stakeholder preferences for the objectives are captured using relative weights. These weights can be developed using a number of methods (Clemen, 1996; Keeney, 2007). In our work, we have determined that the stakeholders find the Analytical Hierarchy Process (AHP) (Saaty, 2006) easy to use. The AHP requires each stakeholder to make a series of pair-wise comparisons between objectives and indicate which of the pair is more important and by how much. Table 2 is adapted from Saaty and displays the numerical scale typically used make these comparisons. Table 3 provides the results of one such set of comparisons conducted during the case study. Notice that the responses are inputs to a positive reciprocal matrix whose dominant eigen vector is used to derive the weights of the objectives for each stakeholder. For example, this decision maker has indicated that *Cost of False Positives* is moderately more important than the *Cost of Implementation*. Thus, the analyst has inserted the value of 3 in matrix element (1,2) and its reciprocal 1/3 in matrix element (2,1). This process is repeated until all the pair-wise comparisons are completed and all the matrix elements are populated. The pair-wise comparisons are conducted between objectives within the same impact category and the stakeholders compare them specifically in terms of their relative importance to optimizing their parent impact category, in this example *Cost*. The impact categories themselves are also compared in the same fashion to establish their relative importance to maximizing the overall goal, in this example M*aximizing the Benefits of Detector Deployment*.

Table 2: Integer Scale Used to Conduct Pair-Wise Comparisons, From Saaty, 2006

Intensity of Importance	Definition	Explanation
1	**Equal Importance**	**Two activities contribute equally to the objective**
2	Weak	
3	**Moderate Importance**	**Experience and judgment slightly favor one activity over another**
4	Moderate Plus	
5	**Strong Importance**	**Experience and judgment srongly favor one activity over another**
6	Strong Plus	
7	**Very Strong Importance**	**An activity is favored very strongly over another; its dominance is demonstrated in practice**
8	Very, very Strong	
9	**Extreme Importance**	**The evidence favoring one activity over another is of the highest possible order of affirmation**

Table 3: Sample weighting from the Analytical Hierarchy Process

Cost				
	False Positives	Implementation	Life Cycle and Maintenance	Weights
False Positives	1	3	¼	0.218
Implementation	1/3	1	1/6	0.091
Life Cycle and Maintenance	4	6	1	0.691

Inconsistency .052

The concept of using value tradeoffs and modeling to set Department of Homeland Security priorities has been advocated by Keeney (Keeney, 2007) for strategic planning. The AHP method offers a tremendous counterpart for operational decisions such as the selection of an overall detector deployment plan because it is robust enough to effectively encompass both broad strategic goals and specific tactical goals through its use of an objectives hierarchy. The AHP also provides a mechanism to check and ensure the stakeholders answer relatively consistently through the use of a consistency ratio.

The MIT group asks each stakeholder to individually complete the AHP. This allows for the quantification of each person's preferences which can then be discussed during deliberation.

2.1.4 Developing Value Functions

The next step in developing the objectives hierarchy structure is to develop a simple value rating scheme for the levels of the constructed scales. The stakeholders must establish the relative worth of the different levels of each constructed scale, and in the case where there are uncertainties associated with the decision outcomes, those relative worths must be evaluated with utility theory. Several techniques for developing these functions with utility theory are readily available in the literature (Keeney and Raiffa, 1976; Clemen, 1996; Hughes 1986). In our case study, there are no significant uncertainties associated with the performance capabilities of the decision options (at least in the unclassified version of the information provided to us by DNDO) and we use a simpler subjective rating technique derived from Clemen's ratio technique (Clemen, 1996, pp. 544-545) to assist the stakeholders in creating value functions. In using this technique, the analyst used a 1 to 9 scale similar to the scale used in weighting the objectives (see Figure 1) and asked the stakeholders to identify how much value was added by improving a system's expected outcome by one level on each constructed scale. The stakeholders always started with a worst case scenario and incrementally assessed the increases in value until the best case scenario was achieved for each objective. An example of a value function computed for our case study is shown in Table 4 below.

Table 4: Sample Value Function

Ability to Detect SNM		
Level	**Unweighted Value Function**	**Weighted Value Function**
Poor	0.0000	0.0000
Average	0.1430	0.0915
Good	0.7140	0.4567
Excellent	1.0000	0.6396

Notice that in Table 4 the unweighted value function is between unity for the best possible outcome and zero for the worst possible outcome just as with a utility function. The stakeholder is then prompted to provide input to establish the relative worth of the middle levels on this normalized scale. The unweighted value function is multiplied by the priority ranking (relative weight) for its objective, in this case *Ability to Detect SNM*, to determine the weighted value function. This particular example shows an aversion to any score less than good for *Ability to Detect SNM.*

2.2 Formulating the Decision Options

The second step is to generate the decision options that will be considered. The decision options should be broad enough to cover all realistic alternatives, should be screened for feasibility and ability to meet any absolute requirements (Screening Criteria), and should be specific to the given problem. The total number of decision options should, however, be kept to a reasonable level that does not unnecessarily burden the analysis. The correct number of decision options to consider for each problem will be unique and specific to that problem and the analytical approach should be flexible enough to quickly incorporate additional decision options later in the process if new information or insights warrant it.

In this case study, the decision options consist of different combinations of detector systems and different deployment options.

2.3 Analyzing and Ranking the Decision Options

The third step in the ADP is to analyze and rank the decision options. The expected performances of the each decision option are predicted for each performance measure using whichever modeling, prototype testing, or simulation technique is most appropriate. In our case study, DNDO had already performed a robust set of testing and modeling on the decision options; these were unavailable to us because of their sensitive nature. As an alternative to using actual test data we elicited the expert opinion of our stakeholders who had access to the test results. This method allowed the stakeholders to categorize the performances of the different decision options without revealing sensitive data to unclassified sources. The result was four independent sets of expert opinion, derived from the same data, which indicated four slightly different interpretations of their test results.

A Performance Index (PI) is then calculated for each of the decision options. The performance index for the jth decision option, PI_j, is defined as the sum of values v_{ij}, associated with the jth decision option's values calculated for the ith objective. In equation 1, N refers to the total number of objectives defined for the specific decision problem. This PI calculation is valid for an additive ordinal utility or value function such as ours that meets the criteria of mutual preferential independence as defined by Clemen (Clemen, 1996, 579-580).

$$PI_j = \sum_{i=1}^{N} v_{ij} \quad (1)$$

The performance index is used to rank the decision options for each stakeholder individually. The decision option rankings for each stakeholder along with an analysis of major contributing factors to the ranking are presented to each stakeholder to objectively communicate what each stakeholder prefers and why. Additionally, a sensitivity analysis should accompany the rankings. The sensitivity analysis addresses whether changes in the stakeholder's preferences could affect the final rankings. If the results are revealed to be sensitive to a particular preference, the stakeholder is asked to review their choices to insure that they accurately reflect their preferences.

2.4 The Deliberation

The fourth step in the ADP, the deliberation, allows the stakeholders to review the results of the analysis, discuss their similarities and differences, and work towards a consensus. The analysis is not intended to result in a final decision. Instead, it is designed to facilitate the deliberation by providing each stakeholder with a thorough understanding of how their preferences affect the decision. The effectiveness of ADP in facilitating deliberation has been demonstrated by the MIT group (Koonce, Apostolakis, and Cook, 2008; Apostolakis and Lemon, 2005; Apostolakis and Pickett, 1998) and primarily stems from its ability to allow the stakeholders to understand each other's points of view. The analysis can clearly separate critical points of agreement and disagreement from those that are unimportant which focuses the deliberation on areas critical to reaching a well informed consensus. The end product of the deliberation should be a final decision, although this is not always the result of the initial deliberation. It is common for the stakeholders to view the results of the analysis, gain additional insight into the problem, and ask to revise their preferences accordingly. This may result in an additional deliberation session before the final decision is made. The form of the final decision is not limited to the set of initial decision options. In a previous case study (Apostolakis and Pickett, 1998), as well as this case study, the final decision was a hybrid of different initial decision options that best suited the values of the group.

2.5 Track, Update and Adjust Through Implementation

The ADP method does not stop when the group reaches a consensus. The fifth step of the ADP is to track, update, and adjust the decision as necessary through the implementation stage. As implementation of a decision begins uncertainties in outcomes will diminish which may affect which option is preferred. For example, if DNDO selects and installs a primary detection system in part of a phased implementation plan only to find it does not perform as well as expected, they may wish to reconsider large scale implementation before proceeding. If this possibility is anticipated and planned for, then the ADP can easily become part of a multistage decision model. The ability to anticipate for and make adjustments in the final decision is situational dependant, but as in this case study, it can often be planed for as part of the final decision.

3. THE CASE STUDY

The Safe Port Act of 2006 (Congressional bill H.R. 4954) requires the government to conduct radiological screening of all cargo entering the United States. With $27x10^6$ twenty-foot equivalent units (TEUs)[1] of cargo passing through shipping ports and $8.7x10^6$ loaded truck containers crossing our borders in 2006 (US Dept of Trans. Maritime Administration, 2007) achieving 100% inspection is clearly impossible without serious impacts on trade. The DNDO's initial action to meet this mandate was to procure and deploy radiation portal monitors equipped with Poly-vinyl Toluene (PVT) scintilators at the US's major shipping ports and border crossings for radiological screening. These RPMs provide a high sensitivity to radiation but cannot identify the isotope present in any but the most ideal situations (Stomswold et al, 2003). To provide isotope identification, the DNDO and CBP established a primary/secondary inspection system where containers identified as having a radiation signature are diverted to a secondary inspection area where CBP agents use hand-held radio-isotope identifier devices (RIIDs) (Oxford, 2007) to identify the source of the radiation. Although ultimately effective in conducting radiological screening, the lack of spectroscopic capability for primary inspections leads to an abundance of lengthy secondary inspections, the vast majority of which simply identify NORM in the cargo and are categorized at nuisance alarms(Oxford, 2007; CBP News Release, 2008).

---

[1] One TEU represents the cargo capacity of a standard shipping container 20 feet long and 8 feet wide. The height of a TEU can range from 4.25 feet to 9.5 feet.

3.1 System Requirements

To provide a better chance of SNM detection and cut down on nuisance alarms, the DNDO solicited for industry to develop radiation portal monitors capable of passive gamma ray spectroscopy in 2005 to replace the current systems. The new systems designed for this purpose were required to fit the current inspection architecture and provide the 100% radiological screening required by law. In addition, they should not have lower sensitivity to radiation. Systems meeting these initial constraints were then judged on their expected false positive and false negative rates, implementation and maintenance costs, ruggedness, impact on terminal operations, and other criteria. In 2006, DNDO conducted an initial prototype testing and conducted an initial CBA according to government acquisition rules and procedures (Oxford, 2007).

3.2 The Decision Options

Currently three prototypes remain in competition, two based on sodium-iodide (NaI) scintillators and a third that uses high-purity germanium (HPGe) semi-conductors as an absorption medium. These represent two fundamentally different sets of detection and cost expectations (Knoll, 2000; Ely, Siciliano, and Kouzes,2004). The decision options in our case study are based on generalized capabilities of NaI and HPGe detectors and are not vendor specific.

The Oxford reference (Oxford, 2007) lists the decision options considered by DNDO during the initial CBA. Since then, the decision options have continued to evolve as additional and better cost estimates and prototype testing are completed. The stakeholders participating in this research agreed to the decision options listed in Table 5 as representative of actual decision options currently being considered in their CBA.

Table 5: Decision Options[2]

Option	Name	Explanation
A	No Change	Uses current PVT detectors for primary inspection and hand-held radio-isotope identifier devices (RIIDs) for secondary inspections
B	PVT-NaI	Uses current PVT detectors for primary inspection and replaces RIIDS with NaI based system for secondary inspections
C	NaI-HPGe	Replaces current PVT detectors with NaI detectors for primary inspections and uses high resolution HPGe detectors for secondary inspections
D	Hybrid	Small throughput ports use PVT detectors and large throughput ports use NaI detectors for primary inspections. All ports use HPGe detectors for secondary inspections
E	NaI-NaI	Replaces current PVT detectors with NaI detectors for primary inspections and uses NaI detectors with a longer dwell time for secondary inspections

None of the decision options considered by DNDO used HPGe detectors in a primary inspection mode. Although the initial CBA did consider this possibility, DNDO later determined that the resolving time required for HPGe to complete an inspection was too long for it to be used in this way. DNDO concluded that the longer resolving time required by HPGe would backlog cargo flow through the port to the point of making this option unfeasible (Ely, Siciliano, and Kouzes, 2004).

[2]Acronyms: PVT: Poly-vinyl Toluene scintillator detector, NaI: Sodium-Iodide scintillator detector, HPGe: High Purity Germanium semi-conductor detector, RIIDs: Radio-Isotope Identification Devices

3.3 The Need for Decision Analysis

The CBA completed by DNDO has come under debate by the Government Accountability Office (GAO)(Aloise 2006; Aloise, 2007) and other agencies have been asked to provide additional decision analysis support for the project including the Defense Threat Reduction Agency (DTRA) and the National Academy of Science (Senate Press Release, 2007). DNDO also agreed to work with the MIT group and analyze the problem using the ADP. Specifically, four stakeholders directly involved in DNDO decision making regarding this project agreed to meet with the researcher and complete the ADP.

3.4 The Stakeholders

The primary stakeholders consisted of an Assistant Director, a Principal Deputy Assistant Director, and a Program Manager directly involved in the acquisition process and a Deputy Assistant Director involved in transformation research and development for DNDO and intimately interested in the project. A Deputy Director from CBP was also consulted to gain insight into CBP priorities for the project and preferences. A workshop was held with the group to agree upon an objectives hierarchy as a group. Then the researcher individually met with each stakeholder to complete their objective preferences, value functions, and assessments of decision option outcomes. The group then came back together to deliberate on the results of the analysis and reach a decision.

4. RESULTS

4.1 The Objectives Hierarchy

The first workshop with the DNDO stakeholders resulted in the formation of the objectives hierarchy displayed in Figure 1. The overall goal of *Maximizing Detector Deployment* was divided into three attributes requiring optimization and six independent objectives that would impact the optimization of those attributes.

While deliberating on the formation of the Objectives Hierarchy the *Stakeholder Impact* category brought about a large discussion on how to define this impact on DNDO's decision making. The input of the CBP Agency was clearly influential. As a sister branch of the Department of Homeland Security (DHS) and the end user of the system, all DNDO stakeholders agreed that the level of approval from CBP would be important to their decision. One stakeholder went as far as to say that no system could move forward if CBP didn't approve of it. Further analysis and discussion indicated that the influence of other stakeholders such as the shipping industry and terminal operators all directly influenced the opinions of CBP. Thus, the majority of stakeholders agreed that CBP input was representative of all external stakeholders relevant to their decision model. Stakeholder D disagreed with this grouping scheme and was adamant that the influence of the terminal operators, those that run commercial operations at the ports, should be considered separately. Therefore, an additional objective of optimizing *Terminal Operator Input* was added in this stakeholder's objectives hierarchy.

4.2 The Constructed Scales

The DNDO stakeholders agreed that the objectives listed in Table 6 fully described what the agency was attempting to achieve by investing in new, passive spectroscopic RPMs. The constructed scales and performance measures in Table 6 were also agreed to in the first workshop with the exception that most scales were initially defined with only three levels. Through the course of the analysis, it became clear that four levels were necessary to properly differentiate the expected outcomes of the decision options.

The constructed scales involving measurable costs, false negative and false positive rates were given specific, measurable ranges in the analysis but the actual use of the scales by the stakeholders varied somewhat. This indicated that the true criteria distinguishing between different levels on the constructed scale was slightly flexible and lead to different assessments of system capabilities

Table 6: Constructed Scales and Performance Measures

Objective	Level	Constructed Scale	Performance Measure
CBP Input	4	Approval	Level of CBP Approval for the diecision option
	3	OK-Ambivlant	
	2	Minor Objections	
	1	Major Objections	
Terminal Operator (TO) Input	4	Approval	Level of TO Approval for the diecision option
	3	OK-Ambivlant	
	2	Minor Objections	
	1	Major Objections	
Cost of False Positives	4	Excellent	Expected False Positive (Nuisance Alarm) Rate for containers with Naturally Occuring Radiation (NORM)
	3	Good	
	2	Fair	
	1	Poor	
Implementation Costs	4	Low	Expected cost in dollars per system to purchase
	3	Medium	
	2	Medium-High	
	1	High	
Maintenance and Lifecycle (M&LC) Costs	4	Low	Expected annual maintainance and replacement costs per system
	3	Medium	
	2	Medium-High	
	1	High	
Ability to Detect Radiological Dispersion Device (RDD) Materials	4	Excellent	Expected false negative rate for containers with bare or lightly shielded RDD Materials.
	3	Good	
	2	Fair	
	1	Poor	
Ability to Detect Special Nuclear Materials (SNM)	4	Excellent	Expected false negative rate for containers with bare or lightly shielded SNM
	3	Good	
	2	Fair	
	1	Poor	

4.3 The Weights of the Objectives

Once the stakeholders reached a consensus on the objectives hierarchy and constructed scales the analyst elicited weights for the objectives from each stakeholder using the AHP. Figure 2 shows the weights assigned to the objectives by each stakeholder.

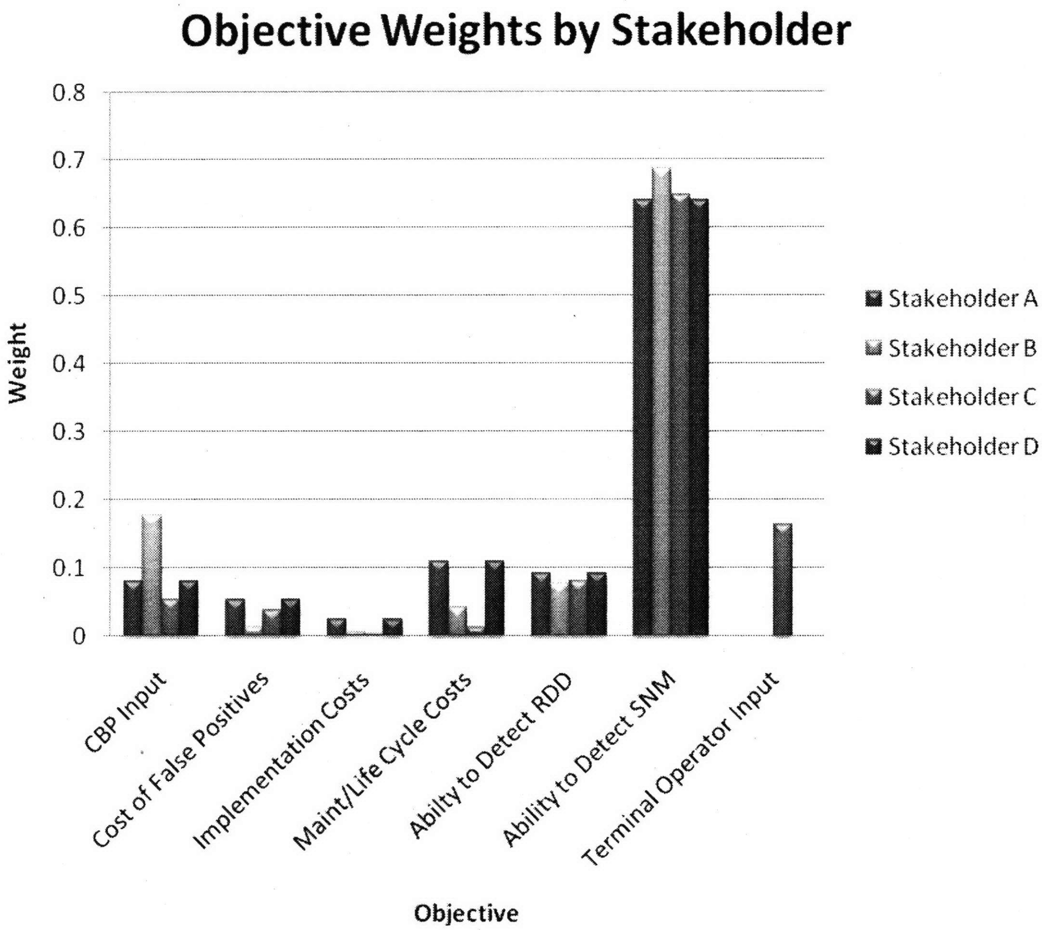

Figure 2: Objective Weights by Stakeholder

The Ability to Detect SNM clearly dominates all other objectives for each stakeholder. This is not unexpected as DNDO reports a similar finding from their Cost-Benefit Analysis. The consequences of a possible nuclear terrorist explosion, though difficult to quantify, are orders of magnitude higher than any other possible consequence. Therefore, DNDO will always choose the decision option that performs best for this objective and only consider the others in the event of tie.

The relative importance of the other objectives varied among the stakeholders. However, all stakeholders ranked *Implementation Costs* last. The typical justification for marginalizing implementation costs was that the majority of the implementation costs are derived from the cost of installation which is approximately a constant across the decision options. Although there are very obvious differences in purchase costs, the importance of these differences is diminished by the installation costs. Some stakeholders were surprised to discover that the *Cost of False Positives* also received a low weight from all stakeholders despite the fact that it was a driving factor to initiate the program. Further discussion revealed that the *Cost of False Positives* was not completely independent from *CBP Input*. A discussion with a CBP deputy director revealed that the opinions of CBP depended on several factors including the effect on stream of commerce, inputs from commercial shippers and terminal operators, and manpower required to run the inspection stations among others. Of these factors, both the stream of commerce and manpower requirement are affected directly by the nuisance alarm rate. Nuisance alarms require secondary inspections which slow down the stream of commerce and require additional CBP personnel to perform.

4.4 The Value Functions

Unweighted value functions for the each objective were elicited from each stakeholder using a variant of the ratio technique described by Clemen (Clemen, 1996). In using this technique, the analyst used a 1 to 9 scale similar to the scale used in weighting the objectives and asked the stakeholders to identify how much value was added by improving a system's capability by one level on each constructed scale. The stakeholders always started with a worst case scenario and incrementally assessed the increases in value until the best case scenario was achieved for each objective. The results of this exercise are displayed in Figure 3 below.

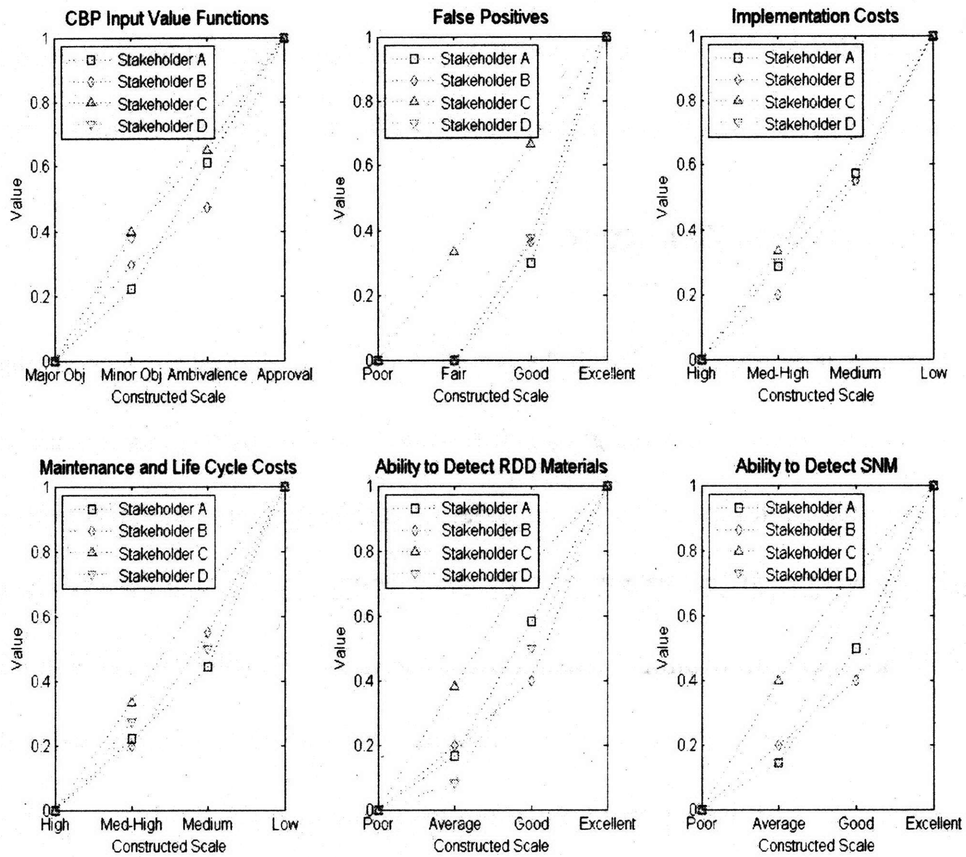

Figure 3: Value Functions for Each Stakeholder

The value functions displayed in Figure 3 are discrete. The values to the stakeholder of each level of the constructed scale are represented by the discrete points in Figure 3. The dotted lines connecting the points are for communication purposes only.

The results indicate that stakeholders A, B and D generally had an aversion to any score less than optimal in each category. Only stakeholder C scored the second best level on a constructed scale above 0.5 in most cases. Further analysis indicated that stakeholder C's perspective on the project varied from that of the other three in that he viewed the most important function of the RPM was as a deterrent while the others viewed it as the actual capability to detect SNM and RDDs. This resulted in stakeholder C's value functions becoming much more linear. The objective in which the different philosophies were most prevalent was the *Cost of False Positives*. Here, most stakeholders believed there was no value in a system that did not at least perform "Good" at minimizing this cost whereas stakeholder C's value function still remained linear.

4.5 The Expected Outcomes

The expected impacts of each decision option were elicited from each stakeholder separately. DNDO has invested significant resources into analyzing and testing the capabilities of the prototypes they are considering and has accumulated a wealth of information regarding their capabilities. Because of the sensitive nature of the data, DNDO did not feel comfortable releasing their specific test results to open sources. However, all four stakeholders were very familiar with the data and could make more general assessments of the expected outcomes using our constructed scales. Their assessments, presented in Table 7, varied despite the fact that each stakeholder had access to the same reports and test results and were sensitive to the stakeholder's interpretation of the data available. For example, the primary attribute for the objective *Minimize the Cost of False Positives* was the expected false positive rate, but the capability of the system to cope with false positives once they occurred was also considered. When additional criteria such as this one were substantial enough to affect the expected outcome for a decision option, the result was discussed among the stakeholders during deliberation. The resulting distribution of expected outcomes among the stakeholders acted as a form of sensitivity analysis for the group as a whole. Additionally, a sensitivity analysis for each stakeholder's results was presented during the deliberation.

Table 7: Expected Outcomes for the Decision Options

Expected Outcomes for the Decision Options				
	Decision Option A (No Change)			
	Stakeholder A	**Stakeholder B**	**Stakeholder C**	**Stakeholder D**
CBP Input	Minor Objections	Minor Objections	Major Objections	Major Objections
False Positives	Poor	Poor	Poor	Poor
Implementation Costs	Low	Low	Low	Low
Maintenance/Life Cycle	Low	Low	Low	Low
RDD Detection	Good	Excellent	Poor	Poor
SNM Detection	Poor	Poor	Poor	Poor
	Decision Option B (PVT-NaI)			
	Stakeholder A	**Stakeholder B**	**Stakeholder C**	**Stakeholder D**
CBP Input	Approval	Minor Objections	Minor Objections	OK-Ambivalent
False Positives	Good	Excellent	Poor	Fair
Implementation Costs	Medium	Medium	Medium	Medium
Maintenance/Life Cycle	Medium	Medium	Medium	Medium-High
RDD Detection	Excellent	Excellent	Fair	Good
SNM Detection	Good	Good	Poor	Poor
	Decision Option C (NaI-HPGe)			
	Stakeholder A	**Stakeholder B**	**Stakeholder C**	**Stakeholder D**
CBP Input	Major Objections	Major Objections	Major Objections	Minor Objections
False Positives	Excellent	Excellent	Fair	Excellent
Implementation Costs	High	High	High	High
Maintenance/Life Cycle	High	High	High	High
RDD Detection	Excellent	Excellent	Good	Excellent
SNM Detection	Excellent	Excellent	Good	Excellent
	Decision Option D (Hybrid)			
	Stakeholder A	**Stakeholder B**	**Stakeholder C**	**Stakeholder D**
CBP Input	Minor Objections	Approval	Approval	OK-Ambivalent
False Positives	Good	Good	Good	Fair
Implementation Costs	Medium	Medium	Medium	Medium-High
Maintenance/Life Cycle	Medium	Medium	Medium	Medium
RDD Detection	Excellent	Excellent	Good	Good
SNM Detection	Good	Excellent	Good	Good
	Decision Option E (NaI-NaI)			
	Stakeholder A	**Stakeholder B**	**Stakeholder C**	**Stakeholder D**
CBP Input	Approval	Approval	Ok-Ambivilant	Minor Objections
False Positives	Excellent	Excellent	Excellent	Good
Implementation Costs	Medium-High	Medium-High	Medium-High	Medium-High
Maintenance/Life Cycle	Medium-High	Medium-High	Medium-High	Medium
RDD Detection	Excellent	Excellent	Excellent	Good
SNM Detection	Excellent	Excellent	Excellent	Good

4.6 The Performance Index

The PI's of the decision options were calculated using equation 1 and in essence summed the values of the decision option's abilities to meet the objectives from the perspective of each stakeholder. The calculation of PI uses an additive value function. Clemen states that this type of function is valid under conditions of *mutual preferential independence*. "An attribute *Y* is said to be preferentially independent of *X* if preferences for specific outcomes of *Y* do not depend on the level of attribute *X*." (Clemen, 1996, p. 579) The attributes of this decision problem meet this criterion and therefore an additive utility function is valid. For example, lower maintenance costs will always be preferable regardless of the level of CBP approval. The PI results from our case study are displayed in Figure 4 and Table 8.

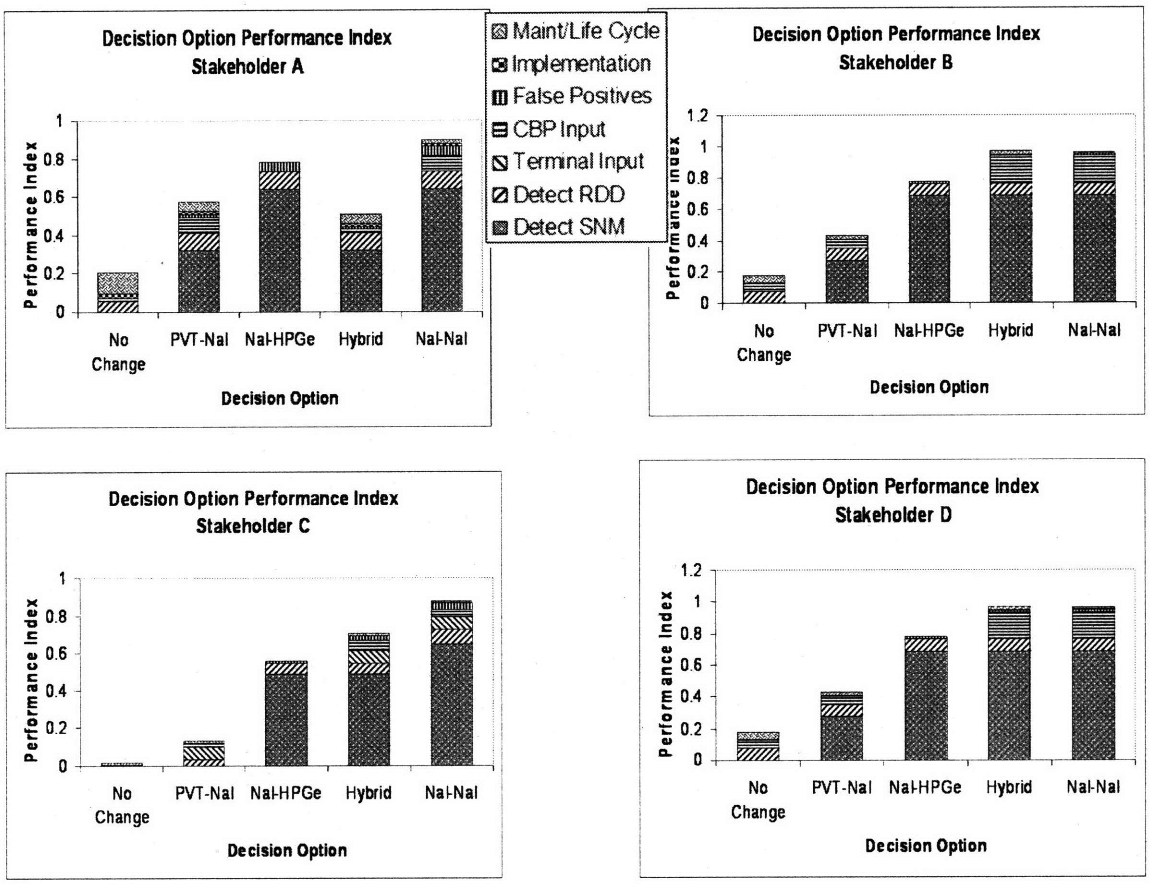

Figure 4: Performance Indices of the Decision Options for each stakeholder

The PI results did not show a clearly preferred option for all stakeholders. Stakeholders A and C preferred NaI-NaI while stakeholder B preferred Hybrid and stakeholder D NaI-HPGe. The PI results did indicate that the No Change and PVT-NaI options were clearly not preferred and should be eliminated from further consideration. For the remaining three options, the preferred decision options clearly demonstrated sensitivity to the *Ability to Detect SNM* for all stakeholders. Stakeholders A and B both rated two decision options excellent in this category and in both cases their answers were sensitive to *CBP Input* and *Maintenance and Life Cycle Costs* with Stakeholder A judging NaI-NaI superior in achieving these objectives and Stakeholder B judging the Hybrid superior. Stakeholder D's preference for the NaI-HPGe option was unique and based on a difference of opinion in the NaI-HPGe's expected outcome for *Ability to*

Detect SNM. These opinion differences were the focus of the deliberation in which the final decision was made.

Table 8: Performance Index Calculations

Performance Index for the Decision Options

Stakeholder A

Objective	A	B	C	D	E
	Decision Option				
Ability to Detect SNM	0.0000	0.3198	0.6396	0.3198	0.6396
Ability to Detect RDD	0.0533	0.0914	0.0914	0.0914	0.0914
Terminal Operator Input	0.0000	0.0000	0.0000	0.0000	0.0000
CBP Input	0.0180	0.0810	0.0000	0.0180	0.0810
Cost of False Positives	0.0000	0.0158	0.0528	0.0158	0.0528
Implementation Costs	0.0254	0.0145	0.0000	0.0145	0.0073
Maintenance and Life Cycle Costs	0.1098	0.0487	0.0000	0.0487	0.0244
Total	**0.2065**	**0.5712**	**0.7838**	**0.5082**	**0.8965**

Stakeholder B

Objective	A	B	C	D	E
	Decision Option				
Ability to Detect SNM	0.0000	0.2747	0.6867	0.6867	0.6867
Ability to Detect RDD	0.0763	0.0763	0.0763	0.0763	0.0763
Terminal Operator Input	0.0000	0.0000	0.0000	0.0000	0.0000
CBP Input	0.0517	0.0517	0.0000	0.1760	0.1760
Cost of False Positives	0.0000	0.0000	0.0133	0.0048	0.0133
Implementation Costs	0.0056	0.0031	0.0000	0.0031	0.0011
Maintenance and Life Cycle Costs	0.0422	0.0232	0.0000	0.0232	0.0084
Total	**0.1758**	**0.4290**	**0.7763**	**0.9701**	**0.9618**

Stakeholder C

Objective	A	B	C	D	E
	Decision Option				
Ability to Detect SNM	0.0000	0.0000	0.4854	0.4854	0.6472
Ability to Detect RDD	0.0000	0.0308	0.0616	0.0616	0.0808
Terminal Operator Input	0.0000	0.0654	0.0000	0.0654	0.0654
CBP Input	0.0000	0.0218	0.0000	0.0545	0.0354
Cost of False Positives	0.0000	0.0000	0.0126	0.0251	0.0377
Implementation Costs	0.0035	0.0024	0.0000	0.0024	0.0012
Maintenance and Life Cycle Costs	0.0128	0.0090	0.0000	0.0090	0.0043
Total	**0.0163**	**0.1294**	**0.5596**	**0.7034**	**0.8720**

Stakeholder D

Objective	A	B	C	D	E
	Decision Option				
Ability to Detect SNM	0.0000	0.0000	0.6396	0.4567	0.4567
Ability to Detect RDD	0.0000	0.0457	0.0914	0.0457	0.0457
Terminal Operator Input	0.0000	0.0000	0.0000	0.0000	0.0000
CBP Input	0.0000	0.0607	0.0304	0.0607	0.0304
Cost of False Positives	0.0000	0.0198	0.0528	0.0000	0.0198
Implementation Costs	0.0254	0.0178	0.0000	0.0076	0.0076
Maintenance and Life Cycle Costs	0.1098	0.0300	0.0000	0.0549	0.0549
Total	**0.1352**	**0.1740**	**0.8142**	**0.6256**	**0.6151**

4.7 The Deliberation.

During the deliberation, the results for each stakeholder were presented to the group for discussion. The stakeholders were in good agreement on the priorities of the objectives which allowed the deliberation to focus on their major differences, namely the expected outcomes for the *Ability to Detect SNM* and *CBP Input* objectives. Five major points of discussion shaped the deliberation.

A critical discussion during the deliberation involved resolving the reasons why stakeholder D rated the NaI-HPGe option higher in *Ability to Detect SNM* and *CBP Input* than the other stakeholders. The discussion revealed a misunderstanding of the operational constraints for secondary inspections. Stakeholder D assumed a longer dwell time for the secondary inspections than the other stakeholders. This longer time would allow the HPGe detectors to outperform the NaI counterparts. Through the course of deliberation, stakeholder D was convinced by the other stakeholders that the shorter dwell time was more realistic, and that CBP would prefer NaI detectors to HPGe and therefore revised his preferences.

A strong discussion during deliberation also focused on the characteristics of the Hybrid Option. Several of the stakeholders questioned stakeholder C's judgment on how well the Hybrid option would perform. It became clear quickly that stakeholder C had misunderstood what combination of detector systems encompassed the hybrid option and therefore misjudged it. Stakeholder C agreed to revise his expected outcomes after the misunderstanding was resolved, a change that raised his PI significantly for the hybrid option. Stakeholder C's top choice remained the NaI-NaI option, but the hybrid moved into second place.

All the stakeholders were surprised to find the lack of importance of implementation costs in the final decision. They had recently spent much time and resources to confirm what those costs would be to support their CBA analysis. These costs were still being debated with other governmental agencies and had become a major focus of their efforts. The stakeholders agreed that if the ADP was the primary decision methodology used for this decision those resources could have been diverted to more important valuable research and saw this as an advantage of the ADP.

Part of the deliberation also involved stakeholder C discussing why he felt it was important to separate the *Stakeholder Impact* category into *CBP Input* and *Terminal Operator Input* instead of grouping both influences under *CBP Input* as the other stakeholders had. Stakeholder C stated that the interests of the terminal operator were strictly business related and directly proportional to throughput. He also observed an aversion to changes in operations and a mistrust of new technology among this stakeholder group. The CBP stakeholders, however, were concerned more with the complexity of the system, the ease of use, and the expected manning requirements for the systems. Stakeholder C did acknowledge the arguments of the other stakeholders that CBP's opinions were influenced by the Terminal Operator opinions as well, but did not think it was a strong enough influence to lump the groups together. In the end, the analysis showed that this dispute had little impact on the final ranking of the decision options and the stakeholders agreed to move on.

Finally, the variance of understanding of CBP preferences among the stakeholders was unexpected. A discussion of each stakeholder's perception of CBP's input was fruitful in clearing additional misunderstandings, primarily stakeholder D's expectation of CBP approving the NaI-HPGe option. Through the discussion it became clear that stakeholder D had not seen the latest position paper from CBP about this program in which the CBP priorities had been updated. After reviewing the new information stakeholder D agreed to revise his responses. Furthermore, the DNDO stakeholders requested that the researcher work with the CBP deputy director responsible for advising DNDO and quantify his input using the ADP as well.

During the deliberation, discussions of other concerns outside the scope of the analysis such as public perceptions of the program as well as the uncertainties in expected outcomes helped to shape the final decision. The stakeholder participation in the ADP helped them to realize that they were not as sure of the expected outcomes as they initially believed themselves to be. In light of this, the group decided to proceed cautiously on a course of action in which they would initially use decision option B, PVT-NaI, to gather additional data from actual field use of the new systems. If the field reports indicated that the NaI systems performed as expected, then the decision would be switched to Hybrid in which NaI systems would be used for primary inspections at major ports. Finally, if the NaI systems performed as expected in a primary function, then DNDO would consider switching to NaI-NaI for all ports and border crossings.

DNDO's final Cost-Benefit Analysis (CBA) is due for a final decision during the summer of 2008. Their preliminary CBA analysis and discussions have good agreement with the results from the ADP model and the organization is currently leaning towards the final decision of this research.

5. CONCLUSION

This paper presented a case study illustrating the use of the Analytic-Deliberative Process for the selection of radiation portal monitors for shipping ports and border crossings. Although the final decision option preferences are similar, the ADP holds an advantage over CBA for these types of decisions in that it quantifies explicitly and separately both objective and subjective influences that affect the decision. The use of an Objectives Hierarchy and the Analytic Hierarchy Process provides a rigorous approach to value modeling that can be implemented and adjusted quickly by executives with minimal technical assistance.

Additionally, the value functions serve the same purpose of CBA's equivalent dollar scales, but can add explicitly the additional information of how important those dollars are to the decision maker. It is clear that attempts to quantify the impact of nuclear terrorism and stakeholder inputs in terms of dollars can be abstract, subjective, and uncertain. Quantities such as attack frequency, consequences, and the impact of countermeasures are clear examples of uncertain and subjective variables that must be combined to give a dollar estimate of the savings in dollars due to increased safety from nuclear terrorism. Much more certainty can be associated with quantifying these outcomes in terms of their value or utility to the decision maker.

Perhaps the greatest strength of the ADP revealed by this research was the effectiveness of the deliberation following the completion of the analysis. Five major points of disagreement among the stakeholders were easily identified and discussed.

Four of the disagreements were the results of misunderstandings between the stakeholders about facts regarding the case study. The deliberation allowed these misunderstandings to be identified quickly and remedied, which led to good agreement between stakeholders who disagreed initially.

The stakeholders did not resolve the final disagreement regarding the influence of terminal operators, but were content to disagree since sensitivity studies indicated their differences had a minimal impact on the final decision. Similarly, sensitivity studies also indicated that the final decision was insensitive to implementation costs; an area in which they had recently focused much of their resources to resolve a debate over these costs with other governmental agencies. This last case highlights an important strength of the ADP in that it can focus the deliberation and further research on areas that truly impact the decision and prevent the wasting of time and resources eliminating uncertainties that are not actually critical to resolve.

One critique of the use of an ADP type decision methodology for public policy making is that it relies on the values of the leaders of the responsible agencies instead of the values of the nation at large. It is true that these two value sets do not necessarily agree. However, the leaders elected and appointed to these positions are selected for their wisdom and great insights into the respective areas. A common issue with CBA use in public policy is that the public's risk perception is often not in good agreement with the actual risk severity. Nor, does it truly represent the values of the entire society but rather a portion of society whose preferences are assumed to represent the greater population. It is fair to say that the leaders of the organizations called to make these public policy decisions have a deeper understanding of these issues than the general public and are charged with the public trust to make value judgments on their behalf. Thus, the arguments supporting the ADP as a legitimate decision methodology for government agencies appear much stronger than those against.

In matters of governmental spending on national security initiatives, subjective influences abound. The difficulties in quantifying these influences with CBA leave them either external to the analysis or hidden within the assumptions. Consensus building can be challenging in these cases which seems to be evident in the case of DNDO's selection of RPM technologies. Therefore, the ADP may be useful to these agencies to better assist in consensus building and moving decisions forward in a timely manner.

6. REFERENCES

Aloise G. 2007. *"Combating Nuclear Smuggling, DHS's Decision to Procure and Deploy the Next Generation of Radiation Detection Equipment Is Not Supported by Its Cost-Benefit Analysis.* Testimony before the Subcommittee on Emerging Threats, Cyber-security, and Science and Technology; Committee on Homeland Security, House of Representatives, Washington D.C.

Aloise G., 2006. *Combating Nuclear Smuggling: DHS's Cost-Benefit Analysis to Support the Purchase of New Radiation Detection Portal Monitors Was Not Based on Available Performance Data and Did Not Fully Evaluate All the Monitors' Costs and Benefits.* Memorandum to Senate and House Appropriation Committees, Washington D.C.

Apostolakis G. E. and D. M. Lemon, 2005. A Screening Methodology for the Identification and Ranking of Infrastructure Vulnerabilities Due to Terrorism, *Risk Analysis.* Vol 25, No 2, 361-376

Apostolakis G. E. and S. E. Pickett, 1998. Deliberation: Integrating Analytical Results into Environmental Decisions Involving Multiple Stakeholders, *Risk Analysis.* Vol 18, No 5, 621-634

Belzer, R. B., 2000, Discounting across generations: necessary not suspect, *Risk Analysis,* Vol 20, 779-92.

Bier V., 2005. *Choosing what to protect: Strategic Defense Allocation against an Unknown Attacker.* Report #05-034. Center for Risk and Economic Analysis of Terrorism Events (CREATE), University of Southern California, Los Angeles, CA.

Clemen R. T., 1996. *Making Hard Decisions.* Duxbury Press, Pacific Grove.

Congressional bill H.R. 4954, Text available at http://thomas.loc.gov.

Ely, J. H., E. R. Siciliano and R. T. Kouzes. 2004. Comparison of NaI(Tl) Scintillators and High Purity Germanium for Vehicle Portal Monitor Applications, *IEEE Nuclear Science Symposium Conference Record,* Vol 3, 1584-1587.

Fischhoff B., et al, 2003. Judged Terror Risk and Proximity to the World Trade Center, *The Journal of Risk and Uncertainty,* Vol 26, No 2/3, 137–151.

French S., Bedford, T., and Atherton E., 2005, Supporting ALARP decision making by cost benefit analysis and multiattribute utility theory, *Journal of Risk Research,* Vol 8, No 3, 207-223.

Hsue, S. T., Sampson T. E., Parker, J .L., Johnson, S. S., Bowersox, D. F., 1980, *Plutonium Isotopic Composition by Gamma-Ray Spectroscopy,* Technical Report LA-8603-MS, Los Alamos.

http://www.cbp.gov/xp/CustomsToday/2006/may/radiation_portal.xml Accessed on 25 April 2008.

Hughes W. R., 1986. Deriving Utilities Using the Analytic Hierarchy Process, *Socio-Economic. Planning Science.* Vol **20**, 393-395.

Keeney R. L. and H. Raiffa. 1976. *Decisions with Multiple Objectives,* John Wiley and Sons, New York.

Keeney R. L., 2007. Modeling Values for Anti-Terrorism Analysis, *Risk Analysis.* Vol 27 No 3, 585-596.

Knoll G., 2000. *Radiation Detection and Measurement*, John Wiley & Sons, Inc, Hoboken

Koonce, A. M., Apostolakis, G.E., and Cook, B.K., 2008. Bulk power risk analysis: Ranking infrastructure elements according to their risk significance, *Electric Power and Energy Systems,* Vol 30, 169-183.

Kouzes, R.T., Ely, Geelhood, Hansen, Lepel, Schweppe, Siciliano, Strom, and Warner, 2003, Naturally Occurring Radioactive Materials and Medical Isotopes at Border Crossings, *National Science Symposium Conference Record, 2003 IEEE*, Vol 2, 1448-1452.

Lakdawalla, D. and G. Zanjani, 2005. Insurance, Self-Protection, and the Economics of Terrorism, *Journal of Public Economics,* Vol 89, No 9-10, 1891-1905.

Layard, R., 1972, *Cost Benefit Analysis*, Penguin Books, Harmondsworth.

National Research Council, 1996. *Understanding Risk: Informing Decisions in a Democratic Society*. National Academy Press. Washington D.C.

Office of Management and Budget, 1992, *Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Program,* Memorandum For Heads Of Executive Departments And Establishments, Circular No. A-94Revise, Washington D.C.

Oxford V. S., 2007. *The Domestic Nuclear Detection Office Cost-Benefit Analysis for Advanced Spectroscopic Portal Monitors.* Testimony before House Homeland Security Committee, Subcommittee on Emerging Threats, Cybersecurity, Science and Technology, Washington D.C.

Oxford V. S., 2007. *The Department of Homeland Security's R&D Budget Priorities for Fiscal Year 2008.* Testimony before House Science Committee, Subcommittee on Technology and Innovation, Washington D.C.

Paté-Cornell E. and Guikema S., 2002. Probabilistic Modeling of Terrorist Threats: A Systems Analysis Approach to Setting Priorities Among Countermeasures, *Military Operations Research*, Vol 7, No 4, 5-20.

Pareto, V., 1896, *Cours D'economie Politique*, Vol 2.

Phillips, G. W., Nagel, D. J. and Coffey,T., 2005, *A Primer on the Detection of Nuclear and Radiological Weapons*, Center for Technology and National Security Policy, National Defense University.

Saaty T. L., 2006. *Fundamentals of Decision Making and Priority Theory with the Analytic Hierarchy Process.* RWS Publications, Pittsburgh

Senate Committee on Homeland Security and Governmental Affairs Press Release, *"Lieberman, Akaka, Thompson, Langevin Urge DHS To Consider Cost-Effectiveness Of Radiation Monitors Before spending $1 billion, "carefully consider" independent audit by GAO, they say".* August 15, 2007.

Shrader-Frechette, K. S., 2000, Duties to future generations, proxy consent, intra- and intergenerational equity: the case of nuclear waste, *Risk Analysis*, Vol 20, 771-78.

Smith V. and D. Hallstrom, 2004. *Designing Benefit-Cost Analysis For Homeland Security Policies*, Report #04-001. Center for Risk and Economic Analysis of Terrorism Events (CREATE), University of Southern California, Los Angeles, CA.

Stavins, R., 2006, *The Costs and Benefits of Public Policies: Fundamental Methods and Common Mistakes,* Lecture, Harvard University, Cambridge.

Stomswold, D. C., Siciliano, E. R., Schweppe, Ely, Milbrath, Kouzes, and Geelhood, 2003. Comparison of Plastic and NaI(Tl) Scintillators for Vehicle Portal Monitor Applications, *Nuclear Science Symposium Record, IEEE,* Vol 2, 1065-1069.

U.S. Department of Transportation, 2002, *National Transportation Statistics 2001,* Bureau of Transportation Statistics, Washington, DC.

US Department of Transportation, Maritime Administration., 2007. *US Water Transportation Statistical Snapshot*, US DOT Office of Policy and Plans, Washington D.C.

US Environmental Protection Agency, 2000, *Guidelines for Preparing Economic Analyses,* EPA Office of the Administrator, Washington D.C.

APPENDIX A: A COMPARISON OF NAI AND HPGE DETECTORS FOR USE IN RADIATION PORTAL MONITORS

The chief technical metrics of judging between detectors are resolution, efficiency, and performance with changing environmental considerations. Detectors used for radiation spectroscopy produce a response function from the incident radiation that can graphically be interpreted as a probably density function for the energy level of the incident radiation. Using this interpretation the resolution is defined as the ratio of the full width of the response function measured at half of the maximum peak value (FWHM) to peak height H_o. (Knoll, 2000)

$$\mathrm{Re}\,solution = \frac{FWHM}{H_0} \qquad \text{(A.1)}$$

HPGe detectors have energy resolutions a factor of 30 better than NaI detectors, with resolutions of <1% and 5-10%, respectively (Knoll, 2000). One reason why the NaI resolution is lower is because its energy resolution is affected by its intrinsic crystal resolution (related to light output), the performance of the photomultiplier tube (PMT), and photocathode. The HPGe detector's resolution, however, is a simple function of the solid state semiconductor material. HPGe's superior resolution gives it a markedly better ability to separate overlapping peaks, detect peaks in the presence of strong background noise, and to make precise calculations of gamma ray energies, thus making it advantageous in situations with masking by Naturally Occurring Radioactive Materials (NORM) or shielding by a high Z substance is likely. For a more in depth discussion on the effect of NORM see appendix B.

The efficiency of a detector is primarily determined by the density of the material and its atomic number or Z value. Because all gammas must be slowed for detection, a detector's efficiency is proportional to the medium's stopping power (Phillips, Nagel, and Coffey, 2005). NaI detectors have a greater gamma absorption capability than HPGe detectors because their Z value is nearly three times that of HPGe (81 as opposed to 32) and therefore have a greater stopping power. Thus, the NaI detector has a higher efficiency overall when comparing detectors of equal size. Finally, although HPGe generally outperforms NaI, HPGe detectors do not detect a majority of the incident gammas at lower energies. Overall, the HPGe detector's peak efficiency is lower than that of a NaI detector of equal size, but with its superior energy resolution and isotopic identification capability it still outperforms a NaI detector. Additionally, the minimum detectable activity (MDA) of source material will be lower for the HPGe detector which makes it more reliable for identifying trace signatures.

For real-world applications the technical advantages of these systems must be balanced out with various practical considerations. The most technically sophisticated system is not the best choice unless it is also cost effective, manufacturable, and robust, among other practical factors. These practical concerns are often dominant in determining the radiation system of choice.

NaI detectors have many practical advantages over HPGe detectors. When we look at both detector systems in terms of cost, the NaI detectors are the clear winner. The direct costs of NaI detectors are about half that of a comparable HPGe detector. When we look at the size of the two detection systems in the context of maneuverability and maintenance, HPGe initially appears to be the clear choice since it is approximately six times smaller than an equivalent NaI system. However, an HPGe detector system requires an external cooling system in order to operate. This fact will not only increase the size of the HPGe system, but also drive the system cost up even more. Additionally, the cooling systems required for HPGe systems are often sensitive to failure and can decrease the overall reliability of the detection system. Additionally, the durability of the HPGe systems is uncertain while the NaI systems have been successfully employed in field conditions for many years. Therefore, the decision makers must be willing to accept some risk in durability if they select the HPGe systems of NaI.

Another practical issue concerns the amount of time needed in order to do a scan. NaI systems can perform a scan relatively quickly (seconds) while the HPGe system requires a longer scan time (minutes) in order to maintain the same level of sensitivity. Thus, from a practical perspective, NaI radiation detection systems appear advantageous over HPGe systems (Ely, Siciliano, and Kouzes, 2004).

Thus, the decision facing DNDO to choose between NaI and HPGe detectors is clearly complex and will have an immense impact on National Security. Technical considerations seem to favor HPGe detectors, while practical considerations favor NaI detectors and stakeholder considerations fall somewhere in between. All relevant factors should be considered and the best choice for this particular application should be selected using a methodology that allows for objective analysis as well as decision maker deliberations. ADP provides such a methodology and may very useful in ensuring the best possible course of action is selected.

APPENDIX B: THE IMPACT OF NATURALLY OCCURRING RADIOACTIVE MATERIALS (NORM) ON DETECTING SPECIAL NUCLEAR MATERIALS AT PORTS AND BORDER CROSSINGS

Countries around the world are deploying radiation detection instruments to interdict the illegal shipment of radioactive material crossing international borders. Of particular concern is the shipment of Special Nuclear Materials (SNM) including various isotopes of plutonium (^{238}Pu, ^{239}Pu, ^{240}Pu and ^{241}Pu) and enriched uranium (^{235}U) which could be used to fashion a nuclear weapon. To detect the presence of these materials at border crossings most countries rely on RPMs to detect the presence of gamma radiation. Radionuclides emit gamma radiation at distinct energy levels which can act as a radiological fingerprint. However, complications can occur in isotope identification if NORM is present. The significance of this complication involves both the frequency in which we encounter NORM in screening cargo at borders and how effectively it can mask SNM.

A quick review of literature reveals that radioactive materials in cargo are fairly common. Typical products containing NORM include those listed in table 9. This table is adopted from Kouzes (Kouzes, et al., 2003) and outlines the materials that most frequently cause alarms at border crossings:

Table 9: Radioactive Materials Causing Alarms at US Border Crossings from Kouzes, 2003

Radioactive Materials Causing Alarms at US Border Crossings	
Material	**% of Alarms**
Kitty Litter	34%
Medical Isotopes	16%
Abrasives	8%
Refractory Material	8%
Scouring Pads	6%
Mica	5%
Potassium/Potash	5%
Granite Slabs	4%
Toilet bowls & tile	4%
Trucks/cars	2%

Additional alarms can occur when passengers are present who have undergone medical treatments involving radioactive isotopes. Kouzes estimates that 1 out of every 2600 Americans carry enough radioactivity from medical treatments to set off typical border crossing radiological alarms.

The effect of NORM on properly identifying SNM sources depends on the type of NORM present and the suspected type of SNM. Most NORM sources originate from four radioisotopes: ^{40}K, ^{226}Ra, ^{238}U, and ^{232}Th. Of these, the most problematic appears to be ^{226}Ra. This isotope emits gamma radiation at 186.2 kev which is close enough to the ^{235}U radiation peak at 185.7 kev to confuse most detectors without very high resolution. This is a serious complication since the ^{235}U peak is weak and provides the only radioactive signature for this isotope. Plutonium is much more radioactive and generally found with several different radioisotopes present. This provides a more distinctive gamma signature which cannot be masked by NORM. Table 10 provides a snapshot of important gamma peaks for plutonium and how NORM radiation peaks would fit into a plutonium spectrum.

Table 10: Plutonium Gamma Spectroscopy Useful Peaks and NORM From Hsue et. al, 1980

Plutonium Gamma Spectroscopy Useful Peaks and NORM				
Region	**Useful Peaks**	**Source**	**Norm Peaks**	**Source**
40-60	43.48	PU-238		
	45.23	PU-240		
	51.63	**PU-239**	**49.5**	**U-238**
	59.54	AM-241	63.8	TH-232
90-105	98.78	PU-239	89.5	TC-99
	98.95	AM-241		
	99.68	PU-238		
	102.97	AM-241		
	103.68	PU-241		
	104.24	PU-240		
120-450	125.29	AM-241	113.5	U-238
	129.9	PU-239		
	148.57	**PU-241**	**140.8**	**TH-232**
	152.68	PU-238		
	160.28	PU-240		
	164.8	PU-241		
	203.54	PU-239	186.2	Ra-226
	208	PU-241		
	332.35	PU-241		
	335.4	AM-241		
	345.01	PU-239		
	370.93	PU-241		
	375.04	PU-239		
	413.71	PU-239		
450-800	642.48	PU-240		
	662.42	AM-241		
	721.99	AM-241		
	766.4	PU-238	1460	K-40

Hence, NORM certainly plays a significant role in assessing the capabilities of a radiation portal monitor's ability to interdict the smuggling of SNM. NORM in cargo appears frequently and must be planned for. Gamma ray spectroscopy techniques can provide an excellent fingerprint for radio-nuclides such as plutonium when NORM is present but may provide unclear results when attempting to identify HEU because of possible masking. Thus, excellent resolution and a well thought out inspection plan are critical to providing protection from SNM smuggling.

APPENDIX C. A DISCUSSION OF THE USE OF COST-BENEFIT ANALYSIS FOR PUBLIC POLICY MAKING

C.1 Historical Background

The first formal thoughts regarding the use of a Cost-Benefit type analysis for public policy decision making are usually attributed to Vilfredo Pareto from whom we get the concept of the Pareto Optimum (Pareto, 1896). The Pareto Optimum is a common-sense notion that considers a policy change an improvement if at least *some* people are made better off and *no one* is made worse off. Its common-sense appeal appears to make it a good criterion for public policy making; however, its standard is impossible to obtain in most real-world situations. In virtually all public policy decisions, someone winds up worse off in order for others to benefit. Thus, most Cost-Benefit Analyses (CBA) today use a revision to Pareto's original work put forth by Nicholas Kaldor and John Hicks in 1939 (Layard, 1972). This revision accepts a policy change if the total gains and total losses of the winners and losers are such that the winners could theoretically compensate the losers and still come out ahead. This is known as the Kaldor-Hicks criterion and is generally used as the foundational criterion for modern day CBA. Since then, CBA has grown into an entire field of study in itself.

CBA has long been used by businesses to analyze potential investments and formally became a part of public policy decision making in 1981. That year President Reagan signed executive order 12291 which mandated "No actions by federal agencies should be taken unless they result in a positive net value to society." This overarching mandate forced the federal government to fully embrace CBA methods but quickly became overly arduous to the agencies required to conduct these analyses. To alleviate this bureaucratic burden, President Clinton signed executive order 12866 in 1993 which required a regulatory analysis to be prepared for all "significant regulatory actions". Significant regulatory actions identified in the order were defined as: having an annual effect on the economy exceeding $100 million, adversely affecting jobs, the environment or public health and safety, seriously interfering with another agency's action, or raising novel legal or policy issues outside legal mandates and Presidential priorities. (US EPA, 2000) Thus, the case study at hand clearly meets both the public health and safety and monetary requirements and is subject to a CBA before the a final decision can be made.

C.2 Decision Metrics

To conduct a CBA, the federal government attempts to quantify all the costs and benefits associated with a proposed policy change. Once these are quantified, there are several decision criteria that exist for determining the best option including Net Present Worth, Benefit-Cost Ratio, and Internal Rate of Return (IRR). The Office of Management and Budget recommended in 1992 that all federal agencies use the Net Present Worth method and this has since become the standard federal approach (OMB, 1992).

In calculating the net present worth of decision alternatives both current and future costs and benefits must be considered simultaneously. To accomplish this, monetary values in the future are adjusted for inflation to yield a net present value. Similarly, the future public benefits (such as the use of a park to be built 10 years from now) are adjusted to their present value through a social discount rate. The moral implications of social discounting have been debated at length. Shrader-Frechette argues that social discounting is dangerous as it overburdens future generations (Shrader-Frechette, 2000) while Belzer argues strongly in favor social discounting as generations have always given and taken from each other (Belzer, 2000). Nonetheless, both inflation and social discounting are generally used today in federally performed CBAs.

C.3 Quantifying Costs

The costs of a decision include actual, physical costs of a decision as well as the indirect costs of negative social impacts among others. The costs of a policy decision can be generally classified into five subcategories: Real-resource compliance costs, Government regulatory costs, social welfare costs, transitional costs and indirect costs (US EPA, 2000).

Real-resource compliance costs include purchase, installation, operation and maintenance of equipment, changes in production or processing capabilities, and the cost of time spent on paperwork. In our case study the real-resource costs would include the purchase price and installation of the detector systems, the manpower costs to the Customs and Border Protection Agency (CBP) to operate the systems, and their associated maintenance costs among others.

Government regulatory costs include things such as the cost of administration, monitoring, and enforcement of regulations. For our case study, these would include the cost of DNDO oversight into the operation of the new detector systems as well as system training for CBP personnel.

Social welfare costs generally refer to losses in consumer and producer surplus due to a rise in price or decrease in output of a good or service. The slowdown in stream of commerce in our case study would fall into this category and is a major concern to the decision makers. As false positives slow down commerce processing through the ports, fewer goods can enter the country and their associated prices will increase.

Transitional costs are temporary costs associated with implementing the new policy. For our case study costs such as implementation and reconfiguring the ports to support the new detector systems could be classified as transitional costs.

Indirect costs include effects new policies may have on markets and society that are not be associated directly with the new policy and can be difficult to measure. These costs may include things such as changes in market structure, (i.e., companies leaving a market due to increased regulation), product quality, (focus diverted from product quality to regulation compliance), or discouraged investment (regulated activity may not be as attractive to investors). One example of an indirect cost in our case study is a high false-positive rate resulting in fewer companies shipping goods to the US because of the hassle of getting their cargo through the ports.

C.4 Quantifying Benefits

The benefits of a policy decision are analyzed by attempting to quantify the Willingness-to-Pay (WTP) and Willingness-to-Accept (WTA) of the public for the different benefits associated with the potential policy change. For example, a CBA conducted by the Department of Transportation may want to assess how much the public is willing to pay in vehicle prices for additional safety features in new automobiles. They may also want to assess how much additional risk of accidents the public is willing to accept to raise the speed limit on a certain stretch of road. Three different types of methods have been developed to quantify benefits in this way, each of which is used in different circumstances in practice. In order of preference the three methods are revealed preferences, stated preferences, and benefit transfer (Stavins, 2006).

Revealed preference methods use people's observed behavior to infer their WTP or WTA for public goods and services. For example, analysts can use revealed preferences to estimate the value of quality school systems and living environments by observing differences in housing prices for the same size and quality of house in different neighborhoods. Similarly, analysts can estimate the value of safety by comparing the salaries of similar jobs performed under different conditions. For example, contractors working in Iraq are paid a premium by the US government due to added hazards of their working environment. Revealed preference methods are generally considered the most accurate. However, the use of this technique depends on the situation and is not always appropriate. In particular, assessing the benefits of the non-use of an asset can be difficult to conduct revealed preferences. Examples would include the value of preserving National Parks for future generations or the National Oil Strategic Reserve.

Stated preference methods usually involved administering a highly structured survey to consumers/citizens to determine the value they place on a good or service. These surveys are subject to the biases of the interviewees and can be very time consuming and expensive when properly done. Nonetheless, for situations in which revealed preference methods are not available these methods are sometimes used.

Benefit transfer methods are considered the least accurate but are more commonly used because they are relatively cheap and fast. The essence of this technique is to find examples of quantified benefit values from other situations and attempt to apply them current decision problem. An example of this type of method is assessing the increase in commerce in one city after an infrastructure improvement project and assuming it will be similar in another city after a similar project is completed. These approximations can be reasonable when the baseline and degree of change between projects are similar, the basic commodities are essentially equivalent, and the affected populations are similar. In our case study a benefit transfer method is necessary to estimate the value of lives saved by purchasing the advanced detection systems and this represents the biggest weakness in the use of CBA techniques for these types of analyses as argued by French (French, Bedford and Atherton, 2005)

C.5 The Value of a Statistical Life (VSL)

The value of a statistical life (VSL) is the term used by analysts to discuss the question of how much value people assess to reductions in the risk of mortality. VSL calculations do not represent the value of life in ethical terms, technical, or economic terms. Rather, it is simply a convention used to express people's stated or revealed marginal valuation for a small change in risk. As an example, the Environmental Protection Agency (EPA) typically uses a VSL of around $6 million in their calculations. This number does not mean an individual would pay $6 million to avoid certain death or accept certain death for $6 million. Instead, it means that a population of several thousand people would be willing to pay $6 million together to prevent the certain death of one of them chosen at random. VSL estimates have a large variance and must be subject to large sensitivity studies. Table 11 below is a list of VSL estimates adopted by the EPA as policy relevant in 2000. From these estimates the EPA has derived a VSL probability distribution as Weibull with a mean of $5.8 million in 1997 dollars (US EPA, 2000).

Table 11:VSL estimates considered policy-relevant.
From *Guidelines for Preparing Economic Analyses*, US EPA, 2000.

VSL Studies adopted by EPA as policy-relevent (Mean values in 1997 dollars)		
Study	**Method**	**Value of Statistical Life**
Kneisner and Leeth (1991 - U.S.)	Labor Market	$0.7 million
Smith and Gilbert (1984)	Labor Market	$0.8 million
Dillingham (1985)	Labor Market	$1.1 million
Butler (1983)	Labor Market	$1.3 million
Miller and Guria (1991)	Contingent Valuation	$1.5 million
Moore and Viscusi (1988)	Labor Market	$3.0 million
Viscusi, Magat and Huber (1991)	Contingent Valuation	$3.3 million
Marin and Psacharopoulos (1982)	Labor Market	$3.4 million
Gegax et al. (1985)	Contingent Valuation	$4.0 million
Kneisner and Leeth (1991 - Australia)	Labor Market	$4.0 million
Gerking, de Haan and Schulze (1988)	Contingent Valuation	$4.1 million
Cousineau, Lecroix and Girard (1988)	Labor Market	$4.4 million
Jones-Lee (1989)	Contingent Valuation	$4.6 million
Dillingham (1985)	Labor Market	$4.7 million
Viscusi (1978, 1979)	Labor Market	$5.0 million
R.S. Smith (1976)	Labor Market	$5.6 million
V.K. Smith (1976)	Labor Market	$5.7 million
Olson (1981)	Labor Market	$6.3 million
Viscusi (1981)	Labor Market	$7.9 million
R.S. Smith (1974)	Labor Market	$8.7 million
Moore and Viscusi (1988)	Labor Market	$8.8 million
Kneisner and Leeth (1991 - Japan)	Labor Market	$9.2 million
Herzog and Schlottman (1987)	Labor Market	$11.0 million
Leigh and Folsom (1984)	Labor Market	$11.7 million
Leigh (1987)	Labor Market	$12.6 million
Garen (1988)	Labor Market	$16.3 million
Derived from EPA (1997) and Viscusi (1992).		

To calculate the benefits in this case study due to the decrease in expected loss of life, an equation such as equation 3 must be used.

$$MCS = \lambda_t \times \overline{F} \times VSL \quad (C.1)$$

where MCS is the Mortality Cost Savings, λ_t is the reduction in the expected number of nuclear terrorism events due the implementation of the decision, $\overline{F}$ is the expected number of fatalities for a single nuclear terrorism event, and VSL is the value of a statistical life. Although it is possible to create estimates of each of these parameters, their uncertainties are unavoidably extreme. This makes the assessment of MCS highly dependent on the assumptions made in estimating its parameters and thus subjective in nature. This unavoidable subjectivity is the biggest problem in using CBA for this case study as it is somewhat hidden in these assumptions. Conversely, the ADP makes the subjectivity of its analysis explicit and more straightforward for discussion.

C.6 A Comparison of Cost-Benefit Analysis and Decision Analysis

French et al. present a good critique and comparison of CBA and DA and argue that DA is more appropriate for making safety decisions in the French nuclear power industry (French, Bedford and Atherton, 2005). The differences in these two theories as presented by French are summarized below.

As described earlier in this text DA is an explicitly subjective decision methodology while CBA attempts to be explicitly objective. DA methods involve value tradeoffs to determine priorities from the perspective of a specific decision maker. CBA attempts to model the values of society as a whole. While the intentions of CBA in this respect are laudable subjectivity inevitably finds it way into the analysis in the form of how the analyst chooses to model societal values. Since CBA is market based, large variances in perceived costs and benefits can abound from different market scenarios for the same good. Clearly different demographics of the US have different aversions to risk, and value everything from natural resources to houses to security differently. How the analyst captures these values can greatly influence the decision.

One perceived advantage of CBA is that it forces consistency in value tradeoffs from decision to decision. Since the analyst in theory does not choose the value preferences that are used in the analysis they remain constant for each new decision that arises. DA gives the decision maker the flexibility to re-evaluate his or her value tradeoffs for each new situation which may be perceived as a problem when making decisions on behalf of the public. The consistency advantage of CBA over DA is mitigated in two ways: first French argues that databanks and records of value tradeoffs can be stored and used as a start point for sensitivity studies in future decision problems, second some degree of changing values should be expected from problem to problem. A classic example of this is the different levels of risk the public is willing to accept when traveling by aircraft as opposed to traveling by car. The public has always demanded much higher safety standards for airline travel than automobile travel even though the airlines have been shown to be much safer (US DOT, 2002).

CBA and DA also differ in their treatment of costs and benefits that are actualized through time. Since CBA is tied to market valuations of costs and benefits it forces the analyst to treat future costs and benefits using an inflation/discount rate or not at all. Other Ad Hoc techniques have been attempted to adjust these figures but none are theoretically justified. Since DA ties costs and benefits to their value to the decision maker it provides more flexibility in the treatment of costs and benefits through time. For Example, French describes one of several techniques used in discounted utility theory (DUT) known as hyperbolic discounting which can model the devaluation of future utility much slower than an equivalent discount rate but still accounts for a decision maker that is *timing averse*.

Finally, when multiple stakeholders are involved DA can formally incorporate a deliberation phase (as it does in our version) in which consensus building can occur. Since CBA theoretically encompasses everyone's values a priori there is no deliberation phase. In reality debate almost always follows these analyses. However, this debate must be framed as a critique of analytical techniques as opposed to a discussion over what the priorities should be for the project. Since the values underlying the decision are debated indirectly this can be a long and slow process as evidenced by this case study.

APPENDIX D. ANALYTIC HIERARCHY PROCESS AND VALUE FUNCTION QUESTIONNAIRES AND RESULT SUMMARIES FOR THE FOUR STAKEHOLDERS.

The following pages contain samples of the questionnaires given to each stakeholder to elicit his values and preferences. The resulting objective weights are calculated using Saaty's relative comparison technique outlined in reference 19 and the value functions were calculated using a variant of Clemen's ratio technique (Clemen, 1996).

The Analytic Hierarchy Process Pair Wise Comparison Worksheet for DNDO's Passive Spectroscopic Portal Monitor Procurement Decision

This worksheet is designed to assist the decision maker in assigning logical weights to the decision criteria he or she is using to decide between prototypes for spectroscopic portal monitor systems.

Instructions: For each pair of criteria presented please circle the pair you feel is more important to the achieving the **specific objective** indicated above the pair. Then circle the number which best describes how much more important you judge that criteria to be.

Use the following chart to interpret what the numbers represent:[1]

Intensity of Importance	Definition	Explanation
1	**Equal Importance**	**Two activities contribute equally to the objective**
2	Weak	
3	**Moderate Importance**	**Experience and judgment slightly favor one activity over another**
4	Moderate Plus	
5	**Strong Importance**	**Experience and judgment srongly favor one activity over another**
6	Strong Plus	
7	**Very Strong Importance**	**An activity is favored very strongly over another; its dominance is demonstrated in practice**
8	Very, very Strong	
9	**Extreme Importance**	**The evidence favoring one activity over another is of the highest possible order of affirmation**

Note: The scale is intended for the decision maker to make evaluations using the odd numbers and bold levels. The even numbers are intended for use when a compromise must be reached between multiple parties completing the exercise.

Objective: <u>Maximize Benefits of Detector Deployment</u>

Criteria: Stakeholder Impact vs. Cost Impact — <u>Comments:</u>

Intensity of Importance:

1 2 3 4 5 6 7 8 9

Criteria: Stakeholder Impact vs. National Security Impact

Intensity of Importance:

1 2 3 4 5 6 7 8 9

Criteria: Cost Impact vs. National Security Impact

Intensity of Importance:

1 2 3 4 5 6 7 8 9

Objective: Minimize Cost

Criteria: Cost of False Positives vs. Implementation Costs

Comments:

Intensity of Importance:

1 2 3 4 5 6 7 8 9

Criteria: Cost of False Positives vs. Maintenance and Life Cycle Costs

Intensity of Importance:

1 2 3 4 5 6 7 8 9

Criteria: Implementation Costs vs. Maintenance and Life Cycle Costs

Intensity of Importance:

1 2 3 4 5 6 7 8 9

Objective: Maximize National Security

Criteria: Capability to Detect RDD Materials vs. Capability to Detect SNM

1 2 3 4 5 6 7 8 9

Quantification of Value Functions associated with Constructed Scales

In this section we will quantify the value functions for each constructed scale agreed upon by the decision maker. The Method for computing the scales is a combination of the Ratio Method as discussed in Clemen.[2] and the pair wise comparison methodology used by Saaty in the Analytic Hierarchy Process[1].

Instructions: For each pair of values from the constructed scale, please circle the number which represents how important it would be to have a system that achieves the higher level of objective fulfillment.

Intensity of Importance	Definition	Explanation
1	**Equal Importance**	**Two activities contribute equally to the objective**
2	Weak	
3	**Moderate Importance**	**Experience and judgment slightly favor one objective fulfillment level over another**
4	Moderate Plus	
5	**Strong Importance**	**Experience and judgment strongly favor one objective fulfillment level over another**
6	Strong Plus	
7	**Very Strong Importance**	**One objective fulfillment level is favored very strongly over another; its dominance is demonstrated in practice**
8	Very, very Strong	
9	**Extreme Importance**	**The evidence favoring one objective fulfillment level over another is of the highest possible order of affirmation**

Note: Again the even numbers are intended for use when compromises are needed between decision makers.

Objective: CBP Input

Constructed Scale:

Major Objections: CBP anticipates significant complications integrating the alternative. CBP considers this alternative no better than the current system or possibly worse.

Minor Objections: CBP would clearly prefer a different alternative than the one chosen but can implement it with minor complications

Ambivalence: CBP finds this alternative acceptable, but it would prefer a different one.

Approval: CBP recommends and approves of the chosen alternative

Criteria: Comments

Major Objections vs. Minor Objections

1 2 3 4 5 6 7 8 9

Minor Objections vs. Ambivalence

1 2 3 4 5 6 7 8 9

Ambivalence vs. Approval

1 2 3 4 5 6 7 8 9

Objective: Minimize Cost of False Positives

Constructed Scale:
Poor: Defined as a False Positive (Nuisance Alarm) Rate of >75% for containers w/ NORM

Fair: Defined as a False Positive (Nuisance Alarm) Rate of 25-75% for container w/ NORM

Good: Defined as a False Positive Rate of 5-25% for containers w/ NORM

Excellent: Defined as a False Positive Rate of <5% for containers w/ NORM

Criteria: Comments:

Poor vs. Fair

1 2 3 4 5 6 7 8 9

Fair vs. Good

1 2 3 4 5 6 7 8 9

Good vs. Excellent

1 2 3 4 5 6 7 8 9

Objective: Minimize Implementation Costs

Constructed Scale:
High: Defined as cost per system >$500,000

Medium: Defined as cost per system $100,000-$500,000

Low: Defined as cost per system <$100,000

Critera: Comments

High vs. Medium

1 2 3 4 5 6 7 8 9

Medium vs. Low

1 2 3 4 5 6 7 8 9

Objective: Minimize Maintenance and Life Cycle (M&LC) Costs

Constructed Scale:
High M&LC: Defined as cost per system >$80,000

Medium M&LC: Defined as cost per system $20,000-$80,000

Low M&LC: Defined as cost per system <$20,000

Criteria: Comments

High M&LC vs. Medium M&LC

1 2 3 4 5 6 7 8 9

Medium M&LC vs. Low M&LC

1 2 3 4 5 6 7 8 9

Objective: Maximize Capability to detect Radiological Dispersion Device (RDD) Materials

Constructed Scale:
Poor RDD Detection: Defined as false negative rate >20% for design basis scenarios

Average RDD Detection: Defined as false negative rate 5-20% for design basis scenarios

Good RDD Detection: Defined as false negatives 2-5% for design basis scenarios

Excellent RDD Detection: Defined as false negatives 2-5% for design basis scenarios

Criteria: Comments:

Poor RDD Detection vs. Medium RDD Detection

1 2 3 4 5 6 7 8 9

Medium RDD Detection vs. Good RDD Detection

1 2 3 4 5 6 7 8 9

Good RDD Detection vs. Excellent RDD Detection

1 2 3 4 5 6 7 8 9

Objective: Maximize Capability to detect Special Nuclear Materials (SNM)

Constructed Scale:
Poor SNM Detection: Defined as false negative rate >20% for design basis scenarios

Average SNM Detection: Defined as false negative rate 5-20% for design basis scenarios

Good SNM Detection: Defined as false negatives 2-5% for design basis scenarios

Excellent SNM Detection: Defined as false negatives <2% for design basis scenarios

Criteria: Comments:

Poor SNM Detection vs. Medium SNM Detection

1 2 3 4 5 6 7 8 9

Medium SNM Detection vs. Good SNM Detection

1 2 3 4 5 6 7 8 9

Good SNM Detection vs. Excellent SNM Detection

1 2 3 4 5 6 7 8 9

D.1 Summary of Results from Questionnaires

Summary of Analytical Hierarchy Process Results for Stakeholder A

Impact Categories				
	Stakeholders	Cost	National Security	Weights
Stakeholders	1	1/3	1/7	0.081
Cost	3	1	1/5	0.188
National Security	7	5	1	0.731

Inconsistency= .062

Cost				
	False Positives	Implementation	Life Cycle and Maintenance	Weights
False Positives	1	3	1/3	0.281
Implementation	1/3	1	1/3	0.135
Life Cycle and Maintenance	3	3	1	0.584

Inconsistency= .13

National Security			
	Ability to Detect RDD	Ability to Detect SNM	Weights
Ability to Detect RDD	1	1/7	0.125
Ability to Detect SNM	7	1	0.875

Inconsistency= 0

Objectives	**Weight**
Ability to Detect SNM	0.63963
Cost of Life Cycle and Maintenance	0.10979
Ability to Detect RDD	0.09138
CBP Input	0.08100
Cost of False Positives	0.05283
Cost of Implementation	0.02538

Summary of Analytical Hierarchy Process Results for Stakeholder B

Attributes				
	Stakeholders	Cost	National Security	Weights
Stakeholders	1	4	1/6	0.176
Cost	1/4	1	1/9	0.061
National Security	6	9	1	0.763

Inconsistency= .104

Cost				
	False Positives	Implementation	Life Cycle and Maintenance	Weights
False Positives	1	3	1/4	0.218
Implementation	1/3	1	1/6	0.091
Life Cycle and Maintenance	4	6	1	0.691

Inconsistency .052

National Security			
	Ability to Detect RDD	Ability to Detect SNM	Weights
Ability to Detect RDD	1	1/9	0
Ability to Detect SNM	9	1	8/9

Inconsistency= 0

Objectives	Performance Index
Ability to Detect SNM	0.68670
CBP Input	0.17600
Ability to Detect RDD	0.07630
Cost of Life Cycle and Maintenance	0.04215
Cost of False Positives	0.01330
Cost of Implementation	0.00555

Summary of Analytical Hierarchy Process Results for Stakeholder C

Attributes				
	Stakeholders	Cost	National Security	Weights
Stakeholders	1	7	1/7	0.197
Cost	1/7	1	1/8	0.051
National Security	7	8	1	0.752

Inconsistency= .362

Cost				
	False Positives	Implementation	Life Cycle and Maintenance	Weights
False Positives	1	7	5	0.701
Implementation	1/7	1	1/7	0.059
Life Cycle and Maintenance	1/5	7	1	0.240

Inconsistency .283

National Security			
	Ability to Detect RDD	Ability to Detect SNM	Weights
Ability to Detect RDD	1	1/8	0.111
Ability to Detect SNM	8	1	0.889

Inconsistency= 0

Stakeholder Impact			
	Ability to Detect RDD	Ability to Detect SNM	Weights
CBP Input	1	1/7	0.125
Terminal Operator Input	7	1	0.875

Inconsistency= 0

Objectives	**Performance Index**
Ability to Detect SNM	0.6685
Terminal Operator Input	0.1724
Ability to Detect RDD	0.0835
Cost of False Positives	0.0358
CBP Input	0.0246
Cost of Life Cycle and Maintenance	0.0122
Cost of Implementation	0.0030

Summary of Analytical Hierarchy Process Results for Stakeholder D

Impact Categories				
	Stakeholders	Cost	National Security	Weights
Stakeholders	1	1/3	1/7	0.081
Cost	3	1	1/5	0.188
National Security	7	5	1	0.731

Inconsistency= .062

Cost				
	False Positives	Implementation	Life Cycle and Maintenance	Weights
False Positives	1	3	1/3	0.281
Implementation	1/3	1	1/3	0.135
Life Cycle and Maintenance	3	3	1	0.584

Inconsistency= .13

National Security			
	Ability to Detect RDD	Ability to Detect SNM	Weights
Ability to Detect RDD	1	1/7	0.125
Ability to Detect SNM	7	1	0.875

Inconsistency= 0

Objectives	**Weight**
Ability to Detect SNM	0.63963
Cost of Life Cycle and Maintenance	0.10979
Ability to Detect RDD	0.09138
CBP Input	0.08100
Cost of False Positives	0.05283
Cost of Implementation	0.02538

Summary of Unweighed Value Function Results for Stakeholder A

CBP Input	
Level	**Value**
Major Objections	0.000
Minor Objections	0.222
Ambivalence	0.611
Approval	1.000

Life Cycle and Maintenance Costs	
Level	**Value**
High	0.000
Medium-High	0.222
Medium	0.444
Low	1.000

Cost of False Positives	
Level	**Value**
Poor	0.000
Fair	0.000
Good	0.300
Excellent	1.000

Implementation Costs	
Level	**Value**
High	0.000
Medium-High	0.286
Medium	0.572
Low	1.000

Ability to Detect RDD	
Level	**Value**
Poor	0.000
Average	0.167
Good	0.583
Excellent	1.000

Ability to Detect SNM	
Level	**Value**
Poor	0.000
Average	0.143
Good	0.500
Excellent	1.000

Summary of Unweighted Value Function Results for Stakeholder B

CBP Input	
Level	**Value**
Major Objections	0.000
Minor Objections	0.294
Ambivalence	0.471
Approval	1.000

Life Cycle and Maintenance Costs	
Level	**Value**
High	0.000
Medium-High	0.200
Medium	0.550
Low	1.000

Cost of False Positives	
Level	**Value**
Poor	0.000
Fair	0.000
Good	0.364
Excellent	1.000

Implementation Costs	
Level	**Value**
High	0.000
Medium-High	0.200
Medium	0.550
Low	1.000

Ability to Detect RDD	
Level	**Value**
Poor	0.000
Average	0.200
Good	0.400
Excellent	1.000

Ability to Detect SNM	
Level	**Value**
Poor	0.000
Average	0.200
Good	0.400
Excellent	1.000

Summary of Unweighted Value Function Results for Stakeholder C

CBP Input	
Level	**Value**
Major Objections	0.000
Minor Objections	0.400
Ambivalence	0.650
Approval	1.000

Life Cycle and Maintenance Costs	
Level	**Value**
High	0.000
Medium	0.471
Low	1.000

Cost of False Positives	
Level	**Value**
Poor	0.000
Fair	0.333
Good	0.667
Excellent	1.000

Implementation Costs	
Level	**Value**
High	0.000
Medium	0.471
Low	1.000

Ability to Detect RDD	
Level	**Value**
Poor	0.000
Average	0.381
Good	0.762
Excellent	1.000

Ability to Detect SNM	
Level	**Value**
Poor	0.000
Average	0.400
Good	0.750
Excellent	1.000

Terminal Operator Input	
Level	**Value**
Major Objections	0.000
Minor Objections	0.400
Ambivalence	0.650
Approval	1.000

Summary of Unweighted Value Function Results for Stakeholder D

CBP Input	
Level	**Value**
Major Objections	0.000
Minor Objections	0.375
Ambivalence	0.750
Approval	1.000

Life Cycle and Maintenance Costs	
Level	**Value**
High	0.000
Medium-High	0.273
Medium	0.500
Low	1.000

Cost of False Positives	
Level	**Value**
Poor	0.000
Fair	0.000
Good	0.375
Excellent	1.000

Implementation Costs	
Level	**Value**
High	0.000
Medium-High	0.300
Medium	0.700
Low	1.000

Ability to Detect RDD	
Level	**Value**
Poor	0.000
Average	0.083
Good	0.500
Excellent	1.000

Ability to Detect SNM	
Level	**Value**
Poor	0.000
Average	0.143
Good	0.714
Excellent	1.000