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METHODOLOGY AND PRELIMINARY MODELS FOR ANALYZING NUCLEAR-SAFEGUARDS DECISIONS

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TABLE OF CONTENTS

PREFACE

This report describes a general analytical tool designed with Lawrence Livermore Laboratory to assist the Nuclear Regulatory Commission in making nuclear safeguards decisions. The approach is based on decision analysis -- a quantitative procedure for making decisions under uncertain conditions. The report:

- Describes illustrative models that quantify the probability and consequences of diverted special nuclear material and the costs of safeguarding the material
- Demonstrates a methodology for using this information to set safeguards regulations (safeguards criteria)
- Summarizes insights gained in a very preliminary assessment of a hypothetical reprocessing plant.

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I. INTRODUCTION AND OVERVIEW

Safeguards Decisions and Objectives

Lawrence Livermore Laboratory (LLL) is developing analytical procedures to assist the Nuclear Regulatory Commission (NRC) in its objective of protecting the public against unacceptable risk of death, injury, or property damage from malevolent use of special nuclear materials (SNM)[1]. Specifically, LLL's methods are designed to help in two different NRC decision-making processes:

- Setting criteria (safeguards standards) for the security of facilities handling SNM
- Assessing individual plants to determine whether the criteria are satisfied.

This report describes analytical techniques developed by LLL and Applied Decision Analysis, Inc. (ADA) to aid the NRC in setting safeguards criteria. Some of the techniques also can be used to summarize the results of the risk assessment procedure applied to a particular facility.

The kind of analysis used to set safeguards criteria is different from the assessment of a given facility in one important way. The distinction is that in setting criteria, one must trade off the benefits of additional safeguards (i.e., reduced risk) with their cost. In other words, the regulator must define the level of risk that is "acceptable." This tradeoff is usually not relevant when deciding whether or not the risk posed by a particular plant meets a prescribed criterion. To make the tradeoff, one must describe the risks involved with the facilities in question. The techniques discussed here for describing risks are equally useful for setting criteria and for assessing individual plants. However, the proposed method for trading off risks with costs is intended primarily for the criteria-setting decisions.

Decision Analysis Approach

Decision analysis provides quantitative tools for assisting decision-makers. The tools are not mathematical formulas or computer programs to replace judgment. Rather, they are tools to be used by the decision-makers so that a large number of factors and uncertainties can be considered consistently and efficiently. For instance, when evaluating the risk posed by a facility with SNM, the decision-makers must consider a wide range of possible threats on the plant and the safeguards system's response to those threats. They also must consider the consequences of the successful diversion of SNM. Probabilistic models can help the decision-maker describe the risk in quantitative terms. Other tools, such as sensitivity analysis, can help the policy-maker identify and then focus on the most important aspects of a particular safeguards decision.

The objective of this report is to describe a method, based on decision analysis, for setting safeguards criteria. The method involves describing risks quantitatively, and balancing them with the costs of reducing the risk. While the models and results discussed in the report concern safeguarding SNM at a nuclear fuel reprocessing facility, the procedures are generally applicable to other fuel cycle facilities or to NRC decision-making on subjects other than safeguards. This report should be viewed as a demonstration of a general methodology, rather than a presentation of an approach to the narrow problem of setting safeguards criteria for a reprocessing plant.

Assumptions in the Analysis

This report contains a substantial amount of quantitative information. These data were developed to illustrate the criteria-setting methodology. To make the examples realistic, the numbers were developed by a few members of the LLL-ADA project team. The numbers reflect the subjective judgment of those individuals; the data were not developed by detailed analysis and should not be regarded as accurate.

The facility chosen for the example is the test bed design [2] for a nuclear fuel reprocessing plant. The design resembles the plant being built by Allied-General Nuclear Services Corporation in Barnwell, South Carolina. The test bed design focuses primarily on the plutonium nitrate storage area. The numbers assessed for this report are based on a plant without a tail-end process for converting plutonium nitrate to plutonium oxide.

We assumed that someone who sets safeguards criteria for a facility will be concerned with two major factors: plant risk and plant costs. We will define the "risk" as the probability of attempts to divert SNM and the consequences of those attempts. Consequences are measured in plant damage, guard deaths, and in public losses caused by malevolent uses of stolen SNM: deaths, property damage, and evacuation. The plant "cost" is broadly defined to include operator costs attributable to safeguards as well as nonmonetary impacts such as employee morale. Our example, however, does not include noneconomic operator costs.

We assumed that the objective of the person setting safeguards criteria was to minimize the sum of the following two factors:

C_D = Diversion Cost, the annual cost of diversion consequences

C_S = Safeguards Cost, the annualized cost of plant safeguards.

In Chapter 3 we will explain how these two different factors may be expressed in common units, so that they can be compared, to aid in setting criteria.

The criteria established for safeguards systems were assumed to be performance-based. For example, we assumed a typical criterion for a Material Control and Accounting (MC&A) system was the probability (P_D) that the MC&A system will detect a particular adversary. For a physical protection (guard) force, a criterion might be the probability (P_I) that an adversary will be stopped. Our illustration of the criteria-setting methodology chooses an optimal level of P_D and P_I for the sample facility.

Therefore, the assumed objective function is:

$$\min_{P_D,\ P_I} \quad C_D + C_S$$

We will also refer to the safeguards cost as safeguards "economics," and to the diversion cost as "risk." Thus, the objective is to minimize both plant economic cost and the risk posed by the facility.

The essence of the safeguards problem is uncertainty. The diversion risk is modeled probabilistically, which means that many of the outputs from the analysis are probability distributions. For instance, the models described here could express the social consequences of the malevolent use of SNM as a probability distribution on public deaths, property damage, or evacuation costs. However, in our illustration of setting safeguards criteria, only the expected values of these probability distributions are used. This is by no means a limitation of the methodology; in fact many of the procedures used in decision analysis were developed to accommodate cases when expected values are judged to be inappropriate decision criteria. However, expected values were used here to simplify the example.

The models of diversion cost consider many types of adversaries; however, we assumed all were motivated to actually divert SNM. We do not consider sabotage or hoax attempts. We also do not consider the deterrent effects of changes in the safeguards system; we assume fixed probabilities for all adversary types.

Uncertainty in the cost or performance of the safeguards system is not modeled explicitly. We have assumed safeguards components have known reliability, and that the facilities comply perfectly with all criteria.

The consequences of diverting SNM are limited to acts of terrorism. We do not consider the consequences of weapons proliferation among foreign governments. The types of consequences considered are in some sense "averaged" over a broad spectrum. For instance, when quantifying consequences of the explosion of a nuclear bomb made with diverted SNM, we consider direct effects such as deaths and damage that are likely to be produced by the detonation of a crude military weapon over a large city. We do not explicitly consider more extreme scenarios such as nationwide anarchy or the total collapse of the U.S. economy because of a single detonation.

Sample Results

The results of the preliminary analysis are presented in many forms, including quantitative results for a particular decision and sensitivity analysis to help understand the models we have developed. As an illustration of typical results, we examine the decision on how much security is "enough." The question is: "How much should be spent to improve the material control system at the plant?" or "At what point does the increased security level cease to be worth the cost?"

Using the decision criterion described earlier -- minimizing safeguards cost plus diversion cost -- is equivalent to increasing MC&A system effectiveness to the point at which the cost of a better MC&A system is larger than the resulting savings in diversion cost. In other words, beyond that point the cost of additional safeguards exceeds the benefits created by reduced risk.

This criterion is demonstrated graphically in Figure 1.1. MC&A system performance is measured by the probability of detecting an attempt to divert nuclear material by a plant employee. Moving to the right in Figure 1.1 means improving the MC&A system. The safeguards and diversion costs are measured on the vertical axis. They are expressed in equivalent dollars, although any comparable units expressing expected utility could be used. The cost (C_S) of increasing MC&A system performance rises rapidly, and probabilities of detection greater than 0.6 are very expensive. The diversion cost (C_D) decreases as the MC&A system is improved. The sum of the safeguards and diversion costs attains its minimum value at P_D^*. If one were setting standards for MC&A performance based on the probability of detection, the level with the highest social benefit is

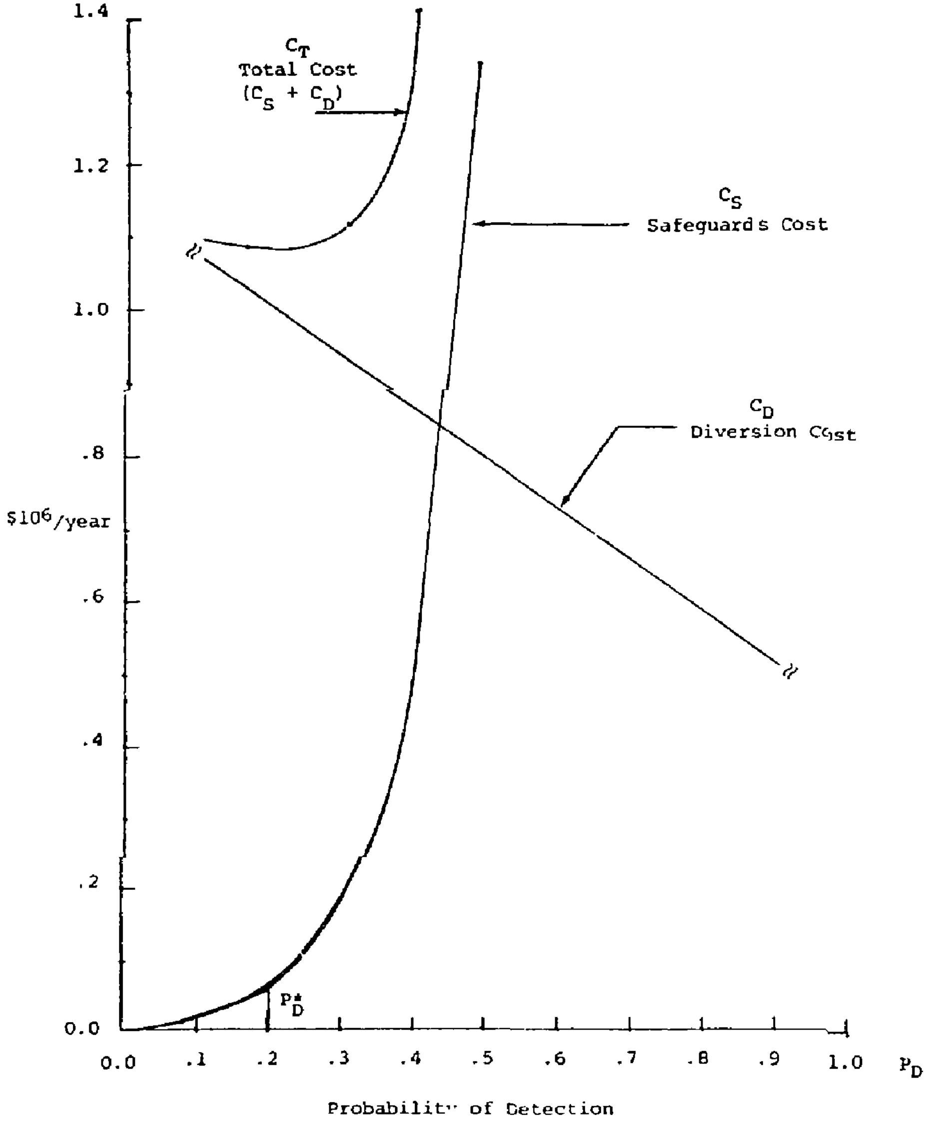

Figure 1.1. Evaluation of MC&A System Performance

P_D^*. A higher performance level is excessively expensive; lower levels allow excess risk of diversion.

The simple graph in Figure 1.1 belies the complexity of quantifying the diversion risk and of making tradeoffs between public and private costs or between dollar costs and public lives saved. These factors will all be considered later. The graph does, however, demonstrate the conceptual criterion for choosing a level of safeguards for the plant.

Illustrative Data

The numbers in this report are derived using relatively simple models of the major factors in the safeguards decision problem. These models are described in Chapters 2, 3, and 4. Even though the highly aggregated models are simple, they serve three important functions:

- They communicate the basic structure of the decision problem to researchers and NRC decision-makers
- They summarize the results of more detailed analyses, such as those produced by the LLL facility assessment procedure
- When analyzed using sensitivity analysis techniques, they will guide the process of refining the detailed models.

The models and data in the report are intended to illustrate the analytical methodology. They will be revised as more complete information becomes available. Nonetheless, these models have produced several insights, which are discussed; however, as mentioned before, the specific numbers in this report are definitely of an illustrative nature.

Conclusions

The preliminary modeling effort has proven to be an effective aid to communication and a guide to further analyses. It has also provided these general insights:

- The preliminary analysis of diversion risk, which is based on explicit treatment of the probability and consequences of a nuclear incident, shows a low expected loss relative to current safeguards expenditures. This conclusion is contrary to conventional wisdom. The reasons behind the result need to be explored.

- Risk attitude (see pages 29 and 30) toward low-probability/high-consequence outcomes is an important consideration for the safeguards policy-maker.
- *Tradeoffs among the multiple dimensions of the problem* (dollars, deaths, injuries) appear to be less sensitive than risk attitude tradeoffs.
- Although not modeled in this report, the uncertainty in safeguards system costs is important; it should not be ignored by focusing only on the uncertainty in diversion risks.

The analysis has generated several preliminary conclusions regarding the models for SNM diversion and the consequences of resulting nuclear incidents. In the Diversion Model, the threats that contribute most to the overall risk appear to be 1) an armed attack on the plant by outsiders and 2) well-equipped, colluding insiders attempting to obtain enough SNM for a bomb. The sophistication of the MC&A system does not influence the success of the first type of threat. The major cost of security procedures is a hypothesized shutdown for inventory caused by the discovery of an inside attempt. As one would expect, the overall frequency of attempts is also significant. The first revisions in the Diversion Model should be in all of those areas.

In the Consequence Model, the most significant factors are the probability and consequences of the successful construction of an atomic weapon, evacuation costs, and the values assigned to preventing extortion attempts. These conclusions depend, of course, on the numbers used in the analysis, although they proved somewhat invariant using a reasonable range of value assessments.

In the model of safeguards technology, the important parameters are MC&A system response to various kinds of tampering by adversaries. The MC&A components we examined appeared to be very vulnerable to tampering. Uncertainty in the cost of some components may also be significant.

Report Organization

Chapters 2 and 3 describe the Diversion and Consequence models respectively. Chapter 4 discusses the Safeguards Technology Model. Chapter 5 demonstrates the integration of these models for the purpose of setting criteria for acceptable risk from safeguarded nuclear facilities.

II. ILLUSTRATIVE DIVERSION MODEL

Evaluation Framework

The major elements and linkages in the safeguards evaluation framework are shown in Figure 2.1. The Diversion Model contains data that characterize the adversary, the type of attempt, and the system's response to that attempt. We shall use the name Diversion Model to mean the combination of the Adversary and Facility submodels. If a diversion attempt is successful, the Public Consequence Submodel describes possible malevolent uses of the stolen material and the consequences. The Utility Submodel assigns values to all possible outcomes, including explicit tradeoffs between cost and diversion risk. We shall call the combination of Public Consequence and Utility submodels the Consequence Model. While the Diversion and Consequence models quantify diversion risk, the Safeguards Technology Model quantifies "economic" costs. The safeguards used at the plant also influence the diversion risk via the Facility Submodel. The meter at the right-hand side of Figure 2.1 shows a combined evaluation for all quantified factors.

To use the safeguards evaluation framework, the policy-maker chooses safeguards components -- levels of physical security and material control performance in the facility -- in such a way to maximize the utility reading on the meter.

Diversion Model Structure

We hypothesize a commercial nuclear fuel reprocessing plant with the ultimate product stored in the form of plutonium nitrate. The model of the probability and consequences of diversion attempt against this facility is shown in Figure 2.2. This model is also described in a report by Brown and Feuerwerger of Decisions and Designs, Inc. [3]. The Diversion Model consists of a probability tree that enumerates the set of

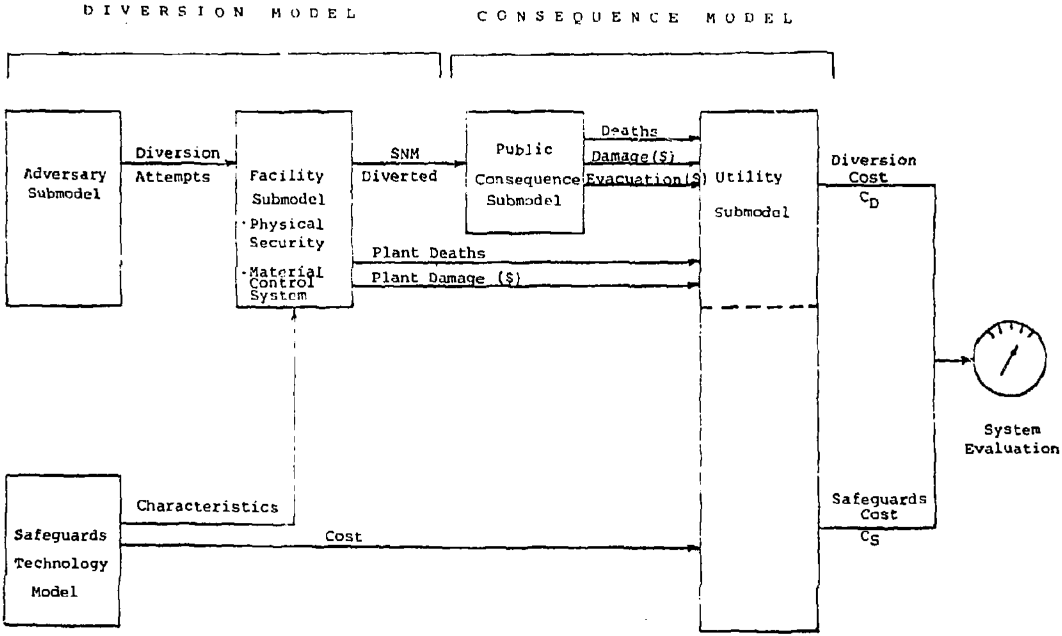

Figure 2.1. Safeguards Evaluation Framework

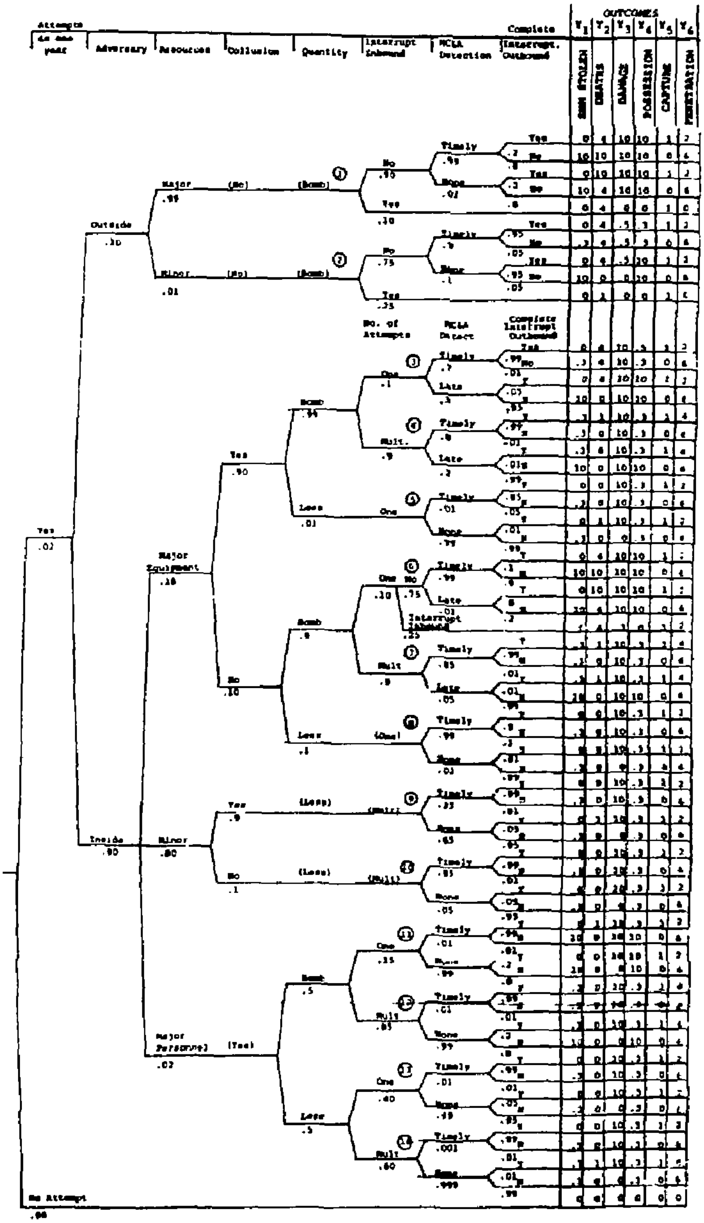

Figure 2.2 Illustrative Diversion Model

events that could result from a specific attempt. The model explicitly considers the following uncertainties: whether or not there will be an attempt, adversary characteristics, the adversary's resources, the possibility of collusion, the target quantity of SNM, and whether or not the attempt is detected and interrupted. The events are described in more detail in Figure 2.3.

Each combination of events at the left of the tree (through "Quantity") defines an "adversary sequence." There are 14 combinations; they are numbered in the tree for later identification. (See reference 4 by I. Sacks for greater detail.)

This model represents the judgments of a few individuals who participated in the development of the LLL facility assessment procedure. Thus, it represents, for those people, a highly-aggregated display of much more detailed information. A similarly-aggregated display could be used effectively to summarize the results of an actual facility assessment.

Each outcome has been evaluated according to six criteria:

- Quantity of SNM stolen [equivalent to kilograms (kg) of plutonium metal]
- Fatalities among plant personnel
- Damages to plant plus shutdown cost
- Maximum amount of material ever in the adversary's possession
- Adversary capture
- Degree of penetration within the plant.

The rules for making value assignments are shown in Figure 2.4. Where the actual value is uncertain, a single number (called the "certain equivalent") was used to represent the range of possible outcomes.

Important Adversary Sequences

One product of the Diversion Model is the expected value for each of the six criteria. The values are computed by "rolling back" the probability tree. (The rollback procedure will be included in our discussion

Attempt

The only attempts considered are those involving theft (diversion) of special nuclear material (SNM). This approach specifically excludes outside attempts to sabotage the plant, internal sabotage or disruption caused by a disgruntled employee, and hoaxes perpetrated against the facility.

The facility in question is the LLL "test bed" design, which is a refinement of the reactor fuel reprocessing plant at Barnwell 2. The output of the plant is assumed to be plutonium nitrate. There is not "tail-end process" for conversion to plutonium oxide.

All probability assessments are made assuming the plant is under normal operating conditions. The probability of attempt covers a one-year period. An attempt may involve single or multiple acts against the facility. The actions in multiple attempts are assumed to cover no more than the one-year period.

Sequence Categories

Adversary--Inside/Outside

An outsider is anyone who does not belong inside the facility. If an adversary is a group of persons, and if any one person is an insider, then the group is considered to be an inside group. If a group has been in any way associated with someone who has provided inside information, then the group is an inside group.

Resources--Major Equipment/Minor Equipment/Major Personnel

If either the plant manager or the Nuclear Material Control Officer (NMCO) is a member of the inside group, then the sequence falls in the category of major personnel. These persons have the knowledge and the authority to defeat the safeguard systems. The group is considered to have major equipment if it does not have either the plant manager or the NMCO, but it does have sufficient tools to breach containment and acquire the SNM. Major equipment is not limited to explosives or sophisticated mechanical devices; it also includes computer software or knowledge (but not the authority) that allows one to penetrate and subvert the computer system. Roughly speaking, major equipment or personnel resources give the adversary the necessary tools to get the job done quickly and efficiently.

An adversary with neither major personnel nor major equipment at its disposal is considered to have minor resources. In general, this adversary does not have the tools to gain direct access to the SNM but rather must create conditions under which the material control and accountability (MC&A) system will yield the material to the adversary. The most likely adversary in this case is the disgruntled employee stealing "nuisance" amounts to disrupt plant activities.

Collusion--Yes/No

When collusion exists, the group size is assumed to be two to three people.

Quantity--Bomb/Less

"Bomb quantity" is define as 10 kg of plutonium metal--sufficient for a crude weapon. "Less" refers to 50-300 grams. This amount could be used in a dispersal weapon.

Number of Attempts--One/Multiple

"One" attempt is self-explanatory. "Multiple" attempts means the adversary intends to steal SNM in small quantities that will, over time, accumulate to desired quantity.

Interruption by Physical Security Inbound--Yes/No

The event is that the adversary is detected and stopped prior to reaching the Material Acquisition Area (MAA). It does not normally apply for Inside Attempts, with the exception of Sequence 6 (outside group with one insider).

Detection by MC&A--Timely/Late/None

Timely detection is assumed to occur when a signal is sent from the MC&A system to physical security in sufficient time to interrupt the sequence. Late detection means a signal is ultimately sent, but not in time to interrupt the adversary. Late detection will be useful in determining the validity of any hoax or extortion attempt involving the claim of possession of SNM.

Complete Outbound Interruption--Yes/No

Complete interruption means that the physical security force prevents SNM from crossing the plant boundary during a given attempt. However, in some cases the "kg Stolen" column indicates .3 kg escaping even with complete interrruption. This represents the scenario where the adversary was caught on, for example, the third of multiple attempts to divert bomb quantity.

Figure 2.3. Definitions of Diversion Model Events

SNM Stolen (Y_1)

1. If escape before detection: target amount.
2. If escape but detected: 0.3 kg equivalent plutonium.
   Exception: Seq. 1, 6, 11: 10 kg equivalent plutonium.
3. If one attempt interrupted: 0 kg.
4. If multiplo attempts, major resources interrupted: 0.3 kg
   Exception: Seq. 14, timely detect: 0 kg.
5. If multiple attempts, minor resources interrupted: 0 kg.

Deaths (Y_2)

1. If escape: 0 deaths.
   Exception Seq. 1, 6 if detected: 10 deaths.
   Exception Seq. 1, 6 if not detected: 4 deaths.
   Exception Seq. 2, 3 if detected: 4 deaths.

2. Otherwise: see assignments.

Plant Damage (Y_3)

Outside Attempt (plus Seq. 6--one insider):
1. If interrupted inbound: $0.
2. If never detected: $0.
3. Otherwise--
   Major resources: $10 million.
   Minor resources: $0.5 million.

Inside Attempt (excluding Seq. 6):
4. If ever detected: $10 million*.
5. Otherwise: $0.

Maximum SNM in Possession (Y_4)

1. If escape before detection: target amount.
2. If interrupted inbound: 0.
3. If one attempt not detected but interrupted: target amount.
4. If multiple attempts not detected but interrupted: 0.3 kg.
5. If detected: 0.3 kg.
   Exception: Seq. 1, 6: 10 kg.
   Exception Seq. 11, not caught: 10 kg.

Capture (Y_5)

1. Yes: 1; No: 0.

Penetration (Y_6)

1. Capture before target reached: 0.
2. Capture after target reached: 2.
3. Capture after leaving facility: 4.
4. No Capture: 6.

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*Inventory Cost: We assume any detected inside attempt will cause an investigation, which will include a two month shutdown to inventory SNM in the plant. Assuming a fixed change rate of 15 percent and a plant cost of $400 million, the debt service alone would be $10 million on the idle plant.

Figure 2.4. Rules for Value Assignments in Diversion Model

of Figure 2.7.) The expected (or mean or average) values for the first three criteria are:

- 0.019 kg SNM diverted/year
- 0.012 plant deaths/year
- $110,000 plant damages/year.

The 14 adversary sequences contribute in varying ways to these expected values, depending on the adversary type, the probability of successful diversion, the amount of SNM stolen, and the plant consequences from the attempt. Figure 2.5 shows the contributions by sequence number.

The 14 sequences can be ranked according to their contributions to the three measures in Figure 2.5. Because many people believe that diverted SNM represents the greatest threat to the public, we have ranked sequences in Figure 2.6 according to the expected amount of SNM diverted. The figure shows that of the expected loss of 0.019 kg/year, Sequence 1 contributes 38 percent of expected SNM diverted. The expected amount diverted in the mode described by Sequence 1, an armed attack on the plant by outsiders, is .0071 kg/year, or 7.1 grams(g)/year. In this sequence, the MC&A system plays no role in preventing the loss. The implication is that if one believes Sequence 1 is more likely than our preliminary probability shows (it is now 5 percent of the probability mass for all sequences), then the importance of improving the MC&A system is small relative to that of improved physical security.

The expected amount of SNM diverted in the mode described by Sequence 4 is .0061 kg/year or 6.1 g/year (33 percent of total). Sequence 4 represents a well-equipped insider. The reason this sequence ranks high compared with others such as Sequence 9 is that Figure 2.2 shows about a 20 percent chance that 10 kg will be stolen successfully by adversaries operating in this mode.

Figure 2.6 shows where additional analysis could pay off. Ninety-six percent of the diverted SNM occurs via Sequences 1, 4, 9, 12, and 3. Based on this preliminary assessment, the models of these sequences should be refined first. This refinement is important because the numbers in

Contribution to Expected Value

Sequence	Diverted SNM (kg)	Plant Deaths	Plant Damages ($\$10^6$)
1	.0071	.0082	.0089
2	.00000048	.000032	.0000037
3	.00087	.00087	.0030
4	.0061	.0022	.027
5	.0000091	.00000030	.0000061
6	.00021	.00025	.00023
7	.00022	.00026	.0028
8	.0000011	0	.00034
9	.0025	.00044	.052
10	.000026	0	.014
11	.00023	.00000028	.000059
12	.0013	0	.00034
13	.000021	0	.000045
14	.000034	.0000011	.000011
TOTAL	.019	.012	.11

Figure 2.5. Sequence Contributions to Expected Diversion Outcomes

Rank	Percent of Total Expected Quantity Diverted	Cumulative Percent	Sequence No. and Description*	
1	38	38	1	Well-equipped outside attempt
2	33	71	4	Well-equipped multiple attempts (bomb)
3	13	84	9	Nuisance attempt by a group
4	7	91	12	Major personnel; multiple attempts (bomb)
5	4.7	96.0	3	Well-equipped; one attempt bomb
6	1.2	97.2	11	Major personnel; one attempt (bomb)
7	1.2	98.4	7	Well-equipped individual; multiple attempts
8	1.1	99.5	6	Well-equipped outside group with one insider; one attempt
9	.18	99.69	14	Major personnel; multiple attempts (dispersal weapon)
10	.14	99.83	10	Nuisance; individual
11	.11	99.94	13	Major personnel; one attempt (dispersal)
12	.049	99.992	5	Well-equipped group; dispersal
13	.006	99.997	8	Well-equipped individual; dispersal
14	.003	1.0	2	Nuisance outside attempt

*Sequences 1 and 2 are outsiders; all others are insiders.

Figure 2.6. Sequence Ranking by Expected Amount of Diverted SNM

these sequences, if changed, would have a greater impact on the overall risk than would changes to numbers in other sequences. The figure also gives an indication about sequences with lower rank. The models of Sequences 2 and 8 would have to change considerably before the expected amount stolen would change by 1 percent: the probabilities in Sequence 2 would have to increase by a factor of 400, and by a factor of almost 200 for Sequence 8.

Link to Consequence Model

The information in the Diversion Model can be presented in a highly condensed form, shown in Figure 2.7. This representation shows the attempt probability and then, conditional on there being an attempt, a probability distribution for the success of the attempt and the amount of SNM diverted. This representation, which is probabilistically equivalent to Figure 2.2 in terms of SNM stolen, shows the information transferred from the Diversion Model to the Consequence Model. Notice that because the Consequence Model is conditioned only on the amount of SNM diverted, those adversaries who cause the greatest amount of SNM to be diverted are presumed to cause the greatest social loss.

The expected quantity of SNM stolen is 19 g/year. This amount is computed from Figure 2.7 by rolling back the probability tree:

$$.019 \text{ kg} = .02\ (.08 \cdot 10 \text{ kg} + .56 \cdot .3 \text{ kg} + .36 \cdot 0 \text{ kg}) + .98 \cdot 0 \text{ kg}.$$

The probability of a successful diversion given an attempt is 64 percent (8 percent + 56 percent).

The number of plant deaths and amount of plant costs associated with the attempt are also shown in Figure 2.7. However, only the expected value (conditional mean) is shown for each amount of SNM diverted.

Reducing the Diversion Model to the distribution shown in Figure 2.7 results in two simplifications. First, it discards a great deal of information about the adversaries and their resources. In the Consequence Model, the assignment of probabilities for various intentions and levels of sophistication is independent of the scenario by which successful diversion took place. In a more refined model, these assignments would be condi-

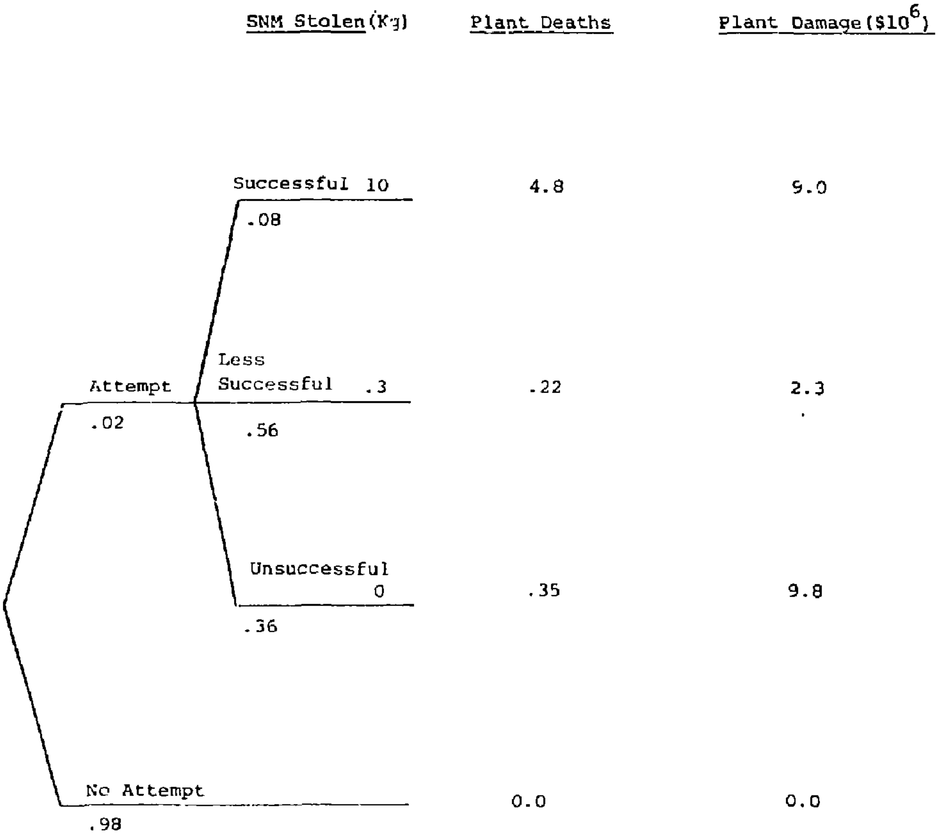


Figure 2.7. Summary of Diversion Model Input to Consequence Model

tional. The second simplification is that expected values for deaths and damages at the plant are used, rather than the entire probability distribution on these consequences. This use of expected values is relatively unimportant. The model gives ranges for plant consequences of 0 - 10 deaths and 0 - $10 million; these values are small relative to the ranges of public deaths and damages in the Consequence Model of 0 - 20,000 deaths and 0 - $4 billion.

III. ILLUSTRATIVE CONSEQUENCE MODEL

Consequence Model Definition

The summary of the Diversion Model, Figure 2.7, appears at the left side of the Consequence Model probability tree in Figure 3.1. Because it includes this diversion summary, the Consequence Model is an aggregated -- but conceptually complete -- representation of the modeled diversion risks, and is in fact a combined Diversion/Consequence Model.

The uncertain events considered in the Consequence Model are: 1) the intended use of the material; 2) the success in making the nuclear device; 3) the location of the resulting nuclear-related incident; 4) whether or not the local population is evacuated; and 5) whether or not the device is detonated. Nonweapon scenarios include fewer possible events, as shown in Figure 3.1. The possible events are defined in Figure 3.2. An index to rules for value assignments is shown in Figure 3.3, and the rules themselves are defined in Figure 3.4.

ADA's original analysis included five possible locations: large city, suburb, farm, dam, and desert. However, making these distinctions does not significantly affect the probability distributions on public deaths and damages. Figure 3.1 shows that the number of deaths is reduced significantly when evacuation preceeds detonation of the bomb or dispersal weapon. However, evacuation is costly: $200 million in the case of a bomb threat and $50 million for the dispersal device -- and in both cases 100 people die as a consequence.

Utility Model

In order to make tradeoffs between safeguards cost and diversion risk, it is helpful to measure consequences in common units. In the Diversion/Consequence Model, the evaluation is in terms of public fatalities and dollar damages, evacuation costs, and deaths and damages

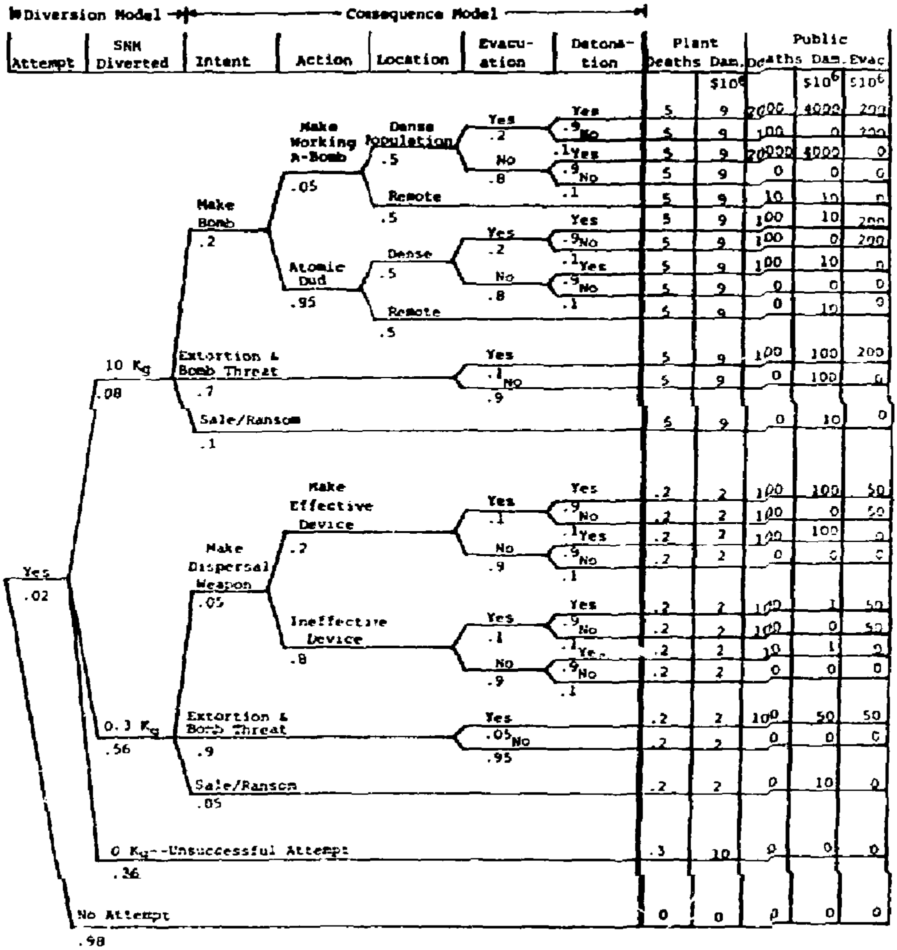


Figure 3.1 Illustrative Diversion/Consequence Model

Attempt

See the definition for the Diversion Model, page 11.

Diverted SNM

Theft is categorized by diverted quantities of SNM equivalent to plutonium metal: 10 kg represents a bomb quantity; 0.3 kg represents a dispersal weapon quantity; 0 kg is an unsuccessful attempt. The probability distributions for the event categories involved with theft are obtained from the Diversion Model, as are the conditional expected values for plant consequences--damages and deaths.

Intent

This category describes the possible end uses for the diverted SNM.

Action

Given that the intent is to make a weapon, either of dispersal or bomb nature, the "Action" category classifies the weapon as effective or ineffective.

Location

If the intent is to make a bomb, this category describes the population in the target area.

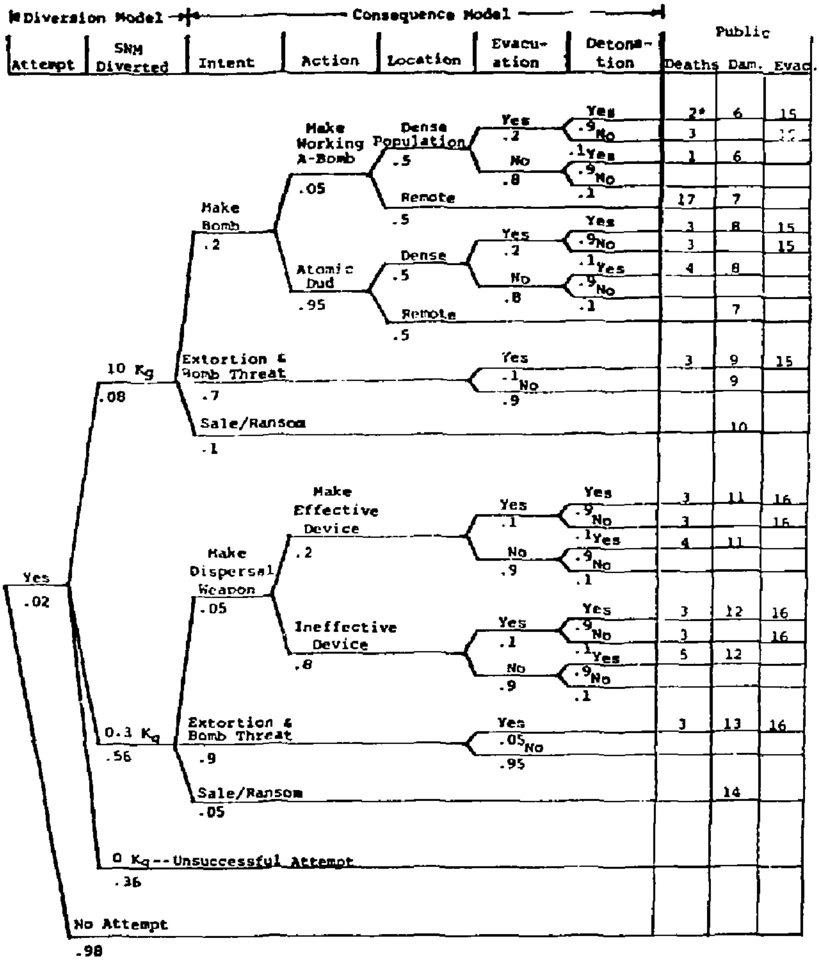
Evacuation

This category represents the outcome of the decision of whether or not to evacuate the exposed population. Evacuation is assumed to be 90 percent effective.

Detonation

This category involves the possible outcome of whether the weapon actually detonates (yes/no). It also includes uncertainty as to the adversary's actions and the weapon's performance.

Figure 3.2. Definitions of Consequence Model Events.



Note: * Refers to explanation number in Figure 3.4. Blank corresponds to a zero entry in Figure 3.1.

Figure 3.3. Index to Value Assignment Rules

Index — Explanation of Value Assignment

1. 20,000 deaths from bomb detonation (no evacuation)

BOMB SIZE: 0.1 to 1 kiloton

Assume detonated at Kearny and California Streets,
in San Francisco

BLAST RESULTS: 14,000 deaths

10 psi (buildings destroyed): 5 square blocks
3 psi (buildings severely damaged): 30 square blocks

Largest office building in area: 7,000 employees

Assume 2 equivalent buildings in which all employees are killed.

MISSILES: 1,000 deaths

Assumption

RADIATION: 5,000 deaths

LD_{50} dose: 5 $mi.^2$

5 $mi.^2$ = 1/9 of San Francisco land area

Assume shielding by buildings is 90 percent effective in reducing casualties.

Assume area populated 5 times average density

$$5 \times 0.1 \; \frac{(700{,}000 = \text{pop. of S.F.})}{9} \approx 40{,}000$$

Based on LD_{50} dose: 20,000 killed by radiation
-15,000 killed by blast and missiles

5,000 deaths by radiation

TOTAL: 20,000 deaths

2. 2,000 deaths from bomb given evacuation

Assume 10 percent of "no evacuation" case:

0.10 x 20,000 = 2,000

* Source: Annals of NY Academy of Sciences, Vol. 105, Article 5, page 831.

Figure 3.4. Explanation of Value Assignments in Consequence Model

Index   Explanation of Value Assignment (continued)

3. 100 deaths caused by panic in evacuation

Assumption

4. 100 deaths caused by effective dispersal weapon

Assume 2/3 of all employees on 1 floor in largest office building receive lethal dose.

$$\frac{2}{3} \cdot \frac{7{,}000 \text{ people}}{45 \text{ floors}} \approx 100 \text{ deaths}$$

Atomic dud bomb assumed to be effective dispersal weapon.

5. 10 deaths due to ineffective dispersal weapon

Assume 10 percent of #4.

6. $\$4 \cdot 10^9$ property damage from bomb detonation

STRUCTURES DESTROYED: $\$300 \cdot 10^6$

1975 cost of largest office building: $\$150 \cdot 10^6$

2 equivalent buildings destroyed $\times\ 2$

$\$300 \cdot 10^6$

STRUCTURES DAMAGED: $\$300 \cdot 10^6$

30 blocks x $\$10 \cdot 10^6$/block $\$300 \cdot 10^6$

MERCHANDISE AND RECORDS: $\$3 \cdot 10^9$

5 times value of structure damaged or destroyed.

CLEANUP: $\$50 \cdot 10^6$

1000 (persons for 12 months) @ $50,000/man-year

TOTAL: $\$3.65 \cdot 10^9 \approx \$4 \cdot 10^9$

(This amount should be increased by prolonged evacuation cost.)

7. $\$10 \cdot 10^6$ property damage given remote bomb detonation

Assumption

Figure 3.4 (continued)

8. $10 · 10^6$ property damage by atomic dud bomb

Assumption

9. $100 · 10^6$ cost of extortion attempt

Assumption

10. $10 · 10^6$ cost of sale/ransom attempt

Assumption

11. $10 · 10^6$ property damage due to effective dispersal weapon

DECONTAMINATION: $10 · 10^6$

50 floors contaminated x 20 cleanup workers/floor

x $1000/week x 10 weeks

DAMAGE TO BUILDING: 90 · 10^6

Assumption

12. $1 · 10^6$ damage due to ineffective dispersal weapon

100 workers x 10 weeks x $1000/week = $$10^6$

13. $50 · 10^6$ cost of extortion given 0.3 kg stolen

Assumption

14. $10 · 10^6$ cost of sale/ransom attempt

Same as #10

15. $200 · 10^6$ evacuation cost given bomb threat

10^6 persons x 2-day evacuation x $100/person-day

16. $50 · 10^6$ evacuation cost given dispersal threat

250,000 persons x 2-day evacuation x $100/person-day

17. 10 deaths due to remote atomic detonation

Assumption

Figure 3.4 (continued)

at the plant. The common numeraire we have selected is dollars because this unit provides a familiar scale. The tradeoff value selected is $\$10^6$/death. This valuation is equivalent to saying that society is willing to pay $\$10^6$ to prevent the loss of one "statistical" life because of a nuclear incident. Changing this tradeoff value by an order of magnitude in either direction can affect the optimal level of safeguards; however, it has little impact on the conclusion of the report.

Sensitivity Analysis

As with the Diversion Model, it is useful to know how much each sequence of events contributes to the expected values. For the combined Diversion/Consequence Model, the expected values are:

- 0.22 deaths
- $350,000 damages plus evacuation cost
- $560,000 equivalent dollars (deaths plus damages).

Figure 3.5 shows the contributions by each sequence to these expected values. The dominant sequences (in descending order) are:

- Bomb detonation with maximum deaths
- Extortion and bomb threat (10 kg stolen, no evacuation)
- Extortion and bomb threat (.3 kg stolen and evacuation)
- Unsuccessful attempt

Major factors in the Consequence Model are shown in Figure 3.6, which is a form of sensitivity analysis. Three major types of consequences are ranked: bomb; dispersal weapon; and evacuation. These are compared to the plant consequences during the attempt.

The annual expected consequence from diversion attempts is $560,000, the amount shown as the base case in Figure 3.6. The last column of the figure shows the contribution of each of the consequences to the $560,000. The percentage contributions are:

	Percent
Bomb (excluding evacuation)	46
Plant consequences	21

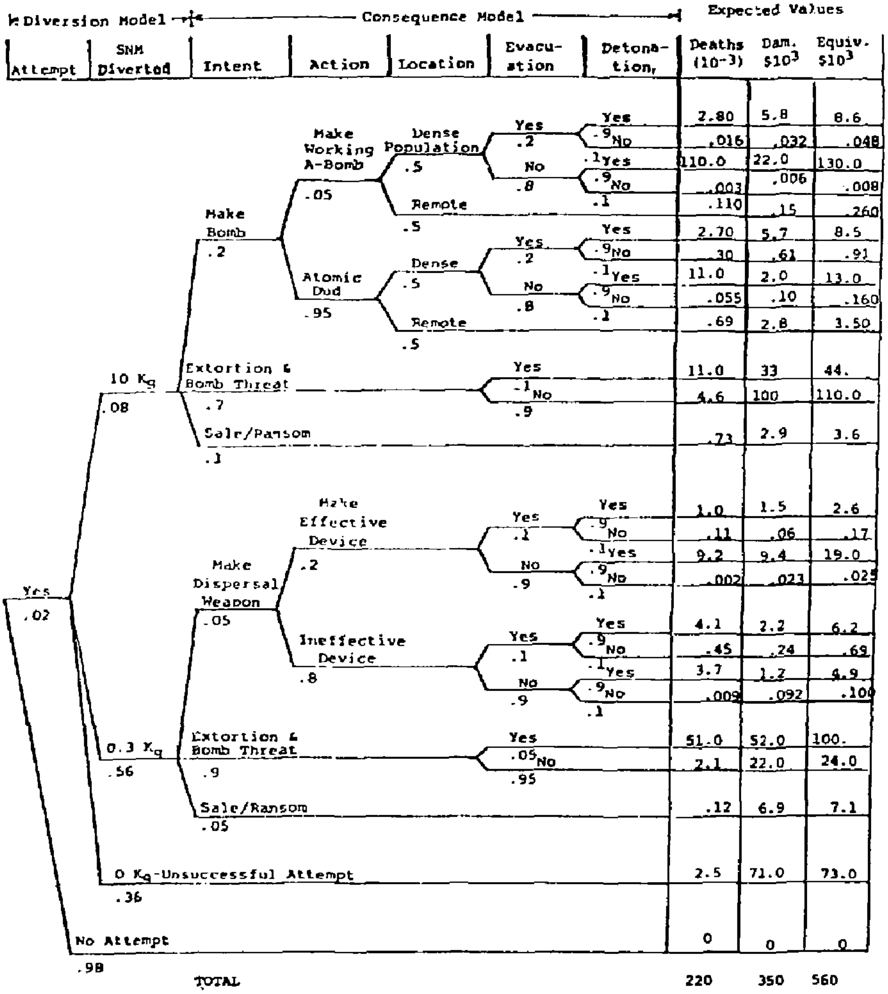


Figure 3.5. Sequence Contributions to Expected Consequences

Variable	Value Base Case	Change When Set to Zero ($)	Total Contributions to Loss ($)
Base Case	$560,000		
Bomb Consequences			
Fission Device			
Deaths	Worst case: 20,000	- 120,000	
Damage	Worst case: $\$4\cdot10^9$	- 20,000	
Atomic Dud	$\$ 10\cdot10^6$	- 13,000	
Extortion	$\$100\cdot10^6$	- 110,000	
Sale/Ransom	$\$ 10\cdot10^6$	- 1,500	
Total			260,000
Plant Consequences			
Deaths	Worst case: 5	- 12,000	
Damage	Worst case: $\$9\cdot10^6$	- 9,000	
Inventory Cost	$\$ 10^7$	- 100,000	
Total			120,000
Evacuation			
Deaths	100	- 69,000	
Damage	$\$200\cdot10^6$ bomb evac. $\$ 50\cdot10^6$ dispersal evac.	- 55,000	
Total			120,000
Dispersal Consequences			
Dispersal Weapon		- 25,000	
Death	Worst case: 100		
Damage	Worst case: 100		
Extortion	$\$ 50\cdot10^6$	- 25,000	
Sale/Ransom	$\$ 10\cdot10^6$	- 6,000	
Total			60,000
TOTAL			560,000

Figure 3.6. Sensitivity Analysis for Consequence Model

Evacuation	21
Dispersal weapon (excluding evacuation)	11
Total	99 (because of rounding).

Figure 3.6 gives the change in expected consequences (combined damage and deaths) when a variable is "zeroed out" of the analysis. The consequences of the bomb or dispersal weapon involve evacuation. Since evacuation is treated separately, evacuation costs are excluded from weapon consequences.

When considering changes to the numbers in the Consequence Model, the reader can approximate the impact of the change by using the sensitivities in Figure 3.6. For instance, a 50 percent increase in the bomb evacuation cost (to 150 deaths; $\$300 \cdot 10^6$ bomb evacuation; $\$75 \cdot 10^6$ dispersal evacuation) will cause an increase of $60,000 (50 percent of $120,000), bringing the total Diversion/Consequence Model loss to $620,000 -- an increase of 11 percent.

The cost of extortion threats is large in both the bomb and dispersal weapon cases. A model of the NRC's and civil authorities' responses to such a threat would help in refining this element of the model. Similarly, an analysis of the conditions under which evacuation is ordered would improve another sensitive model component.

Figure 3.7 summarizes the Diversion/Consequence Model in terms of public and plant consequences: deaths, damages, evacuation and inventory costs. At the bottom of Figure 3.7, we see that combined deaths contribute $230,000 out of $560,000 equivalent consequences. Increasing the tradeoff value between dollars and deaths by 50 percent (to $1,500,000 per death) increases total losses by $115,000, for a new total of $675,000 -- a 21 percent increase.

Comparison of Diversion Risk with Reactor Safety

Risk Profiles

Figure 3.8 gives the complete probabilistic output of the Consequence Model. The three curves in the figure are complementary cumulative prob-

	Expected Equivalent Dollars	Totals ($)
Public Consequences		
Deaths (including evacuation)	220,000	
Property Damage	160,000	
Evacuation Cost	60,000	
Subtotal		440,000
Plant Consequences		
Deaths	12,000	
Damage	9,000	
Inventory Cost	100,000	
Subtotal		120,000
TOTAL		560,000
Combined Public and Plant Consequences		
Deaths (including evacuation)	230,000	
Damages	170,000	
Evacuation Cost	60,000	
Inventory Cost	100,000	
Total		560,000

Figure 3.7. Consequence Sensitivity Summary

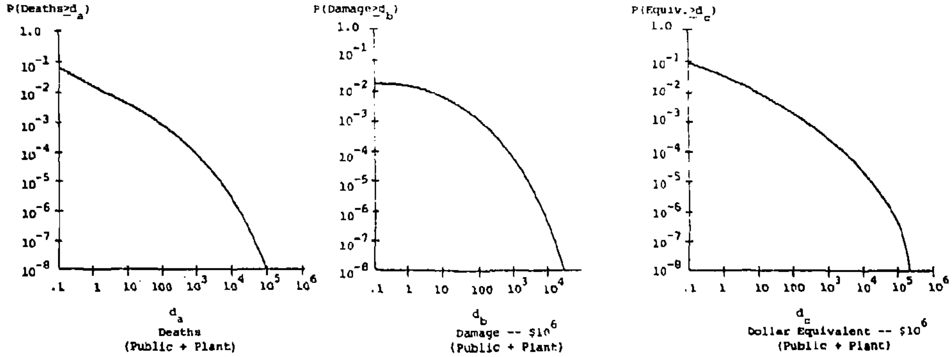


Figure 3.8. Probability Distributions on Consequences

ability distributions for deaths, dollar damages, and the combined consequence measure given in equivalent dollars. These are commonly called "risk profiles." The profiles give the range of possible outcomes and the probability that these outcomes could occur. The curves were derived by plotting the appropriate endpoints and probabilities from Figure 3.1, and then drawing a smooth curve through them.

In previous sections, only the expected value, or mean, for each curve was used. These expected values are:

0.22 deaths

0.34 million dollars damage

0.56 combined dollar equivalent (millions).

The $560,000 combined mean equals the base case value in Figure 3.7.

Consider the curve on the left in Figure 3.8. It says that there is roughly 10^{-3} probability of 10 or more deaths and virtually no chance of deaths exceeding 100,000. Modifying the safeguards system could change the shape of the curve. The preferred direction of change (from a risk reduction viewpoint) is downwards and to the left.

Two fundamental questions that arise in risk/benefit analysis are made apparent by Figure 3.8:

- How can dimensions such as damages and deaths be combined?
- What single number can be used to represent the entire curve?

The difference between the single number and the expected value, which was used earlier, depends on the decision-maker's attitude toward risk. We shall refer to these problems as:

- Combined attributes, and
- Risk attitude.

These problems are important because safeguards decisions ultimately rest on a judgment as to the amount of money to spend to reduce risk. To make that tradeoff, the decision-maker must either explicitly or implicitly state a willingness to pay to prevent loss of life and injuries, and a willingness to pay to prevent low-probability occurrence of these losses.

Compared to risk attitude, the answer to the combined attribute question (tradeoffs between fatalities and dollars) is relatively well established. The most common tradeoff values for a statistical life range from $100,000 to $1,000,000. Either extreme could be used without significantly changing the conclusions in this report. However, the risk attitude judgment has fewer explicitly established precedents. A strong argument can be made that when the range of outcomes is small relative to the total assets of the population at risk, then the mean or expected value of the outcomes is an appropriate criterion. Using this risk criterion, the combined total expected risk is $560,000/year, as we have seen.

Are current safeguards decisions being made consistent with this criterion? Given recent political decisions, plus the resources currently directed towards safeguards research and regulation (which far exceed the amount of expected risk -- $560,000), it seems unlikely that expected values are being used for political decisions. This subject is an important area for further investigation.

Comparison to Reactor Safety

Using the profiles in Figure 3.8, we can compare reprocessing risks with the risks from other processes in the nuclear fuel cycle. Figure 3.9 depicts the three risk profiles from the reprocessing base case. Superimposed on these are similar curves from the Reactor Safety Study, WASH-1400 [5]. The WASH-1400 study considered the risk from 100 reactors. We assume one 1500 metric ton (MT) per day reprocessing facility services roughly 50 reactors. Thus, we have scaled down the risk profiles in WASH-1400 for 100 reactors by a factor of 2.

Figure 3.9 illustrates how the magnitude of reprocessing risks could be compared to other fuel cycle risks. However, the reader

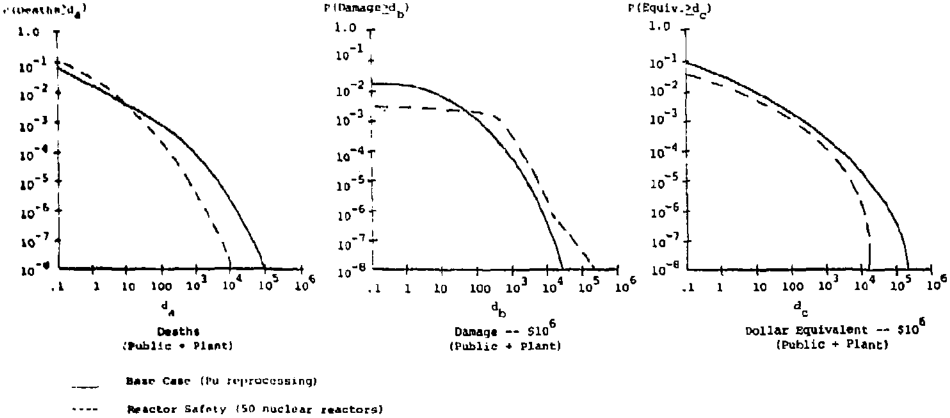


Figure 3.9. Comparison of Reprocessing Risks with Reactor Safety (Illustrative Data)

should be aware that the populations at risk may be different. In the case of a reactor incident, population centers "downwind" from the 50 nuclear plants are at risk. In the case of a reprocessing-related incident, the exposed group is people living and working in areas vulnerable to malevolently-caused nuclear incidents. The magnitude of consequences given a reactor accident may also differ from those in the nuclear incident. Therefore, identical risk profiles do not necessarily imply identical magnitude of risks to the population.

There is a tendency to conclude that reprocessing is "safe enough" when its risk profile falls below the risk profile for all other fuel cycle risks. This assumption, however, is not generally true. The reprocessing risks are at their optimal level when the cost of further reducing the risk equals the equivalent dollar benefit of the reduced risk. In other words, the optimal position of the reprocessing risk profile is when the cost of pushing it toward the origin equals the benefit of that shift. This reprocessing risk should then be combined with reprocessing costs and the costs of the rest of the fuel cycle to yield a total cost for the closed fuel cycle. If this total cost is less than the cost of the alternative -- an open-ended fuel cycle -- then reprocessing is "safe enough." If the alternative costs less, then the risk associated with reprocessing is unacceptable. (This assumes that the overall cost of nuclear power is less than the cost of alternative power sources or of conservation.)

Because of the importance of these concepts in determining the acceptability of risks from reprocessing, we shall develop examples in Chapter 5. We conclude this discussion by emphasizing the point that while Figure 3.9 is useful for comparing risks, it is *not a sufficient means of determining* the acceptability of risks created by reprocessing.

Value of Information

A plant shutdown for inventory is, in effect, an information-gathering operation. The information will be used in making future decisions, *such as changing security measures*. The information as to whether or not SNM is missing could also be used in the evaluation of bomb threats, and it could influence the decision to evacuate given a threat. Using the Diversion and Consequence models, we can compute the expected value of knowing for certain whether or not SNM is missing. This expected value of *perfect information* (EVPI) is then an upper bound on the value of information gained during an inventory shutdown. This exercise will also show the linkage between evacuation and inventory costs -- two sensitive parameters in the model.

Figure 3.10 shows a simple structure for computing the EVPI. We consider an information-gathering experiment; the top branches in the tree correspond to the situation in which an additional inventory is conducted. (We shall assume the yearly inventory is conducted on January 1, 1979, whether or not an inside attempt is made.) After the inventory, it is known whether or not a successful diversion has been carried out. (Assume missing material means diversion.) The next event in the tree concerns the receipt of a threat of malevolent acts. A "real" threat is one issued by adversaries who possess SNM. A hoax is any other type of threat. Then the decision is made whether or not to evacuate; ultimately, there is or is not a detonation. Implicit is an assumption that the bomb detonation is independent of the evacuation decision. The expected loss was calculated as the sum of all deaths and damage costs in Figure 3.1, using the assumption that a threat was sent half the time when weapons were made.

Figure 3.11 shows the rollback values in the tree. Note that in every case, the lowest expected cost is along the "no evacuation" branch. In other words, the best decision is always "do not evacuate," even with perfect information on whether or not SNM is missing. Since the information does not influence the evacuation decision, the value of the information is zero.

If we were to increase the probability that the adversaries could make a successful atomic weapon from [illegible] to 1.0 (see Figure 3.1), then the decision on whether to evacuate with perfect information could switch from "No" to "Yes." In this case, the inventory information would have value. For it to be worth at least $10 million (the cost of the inventory),

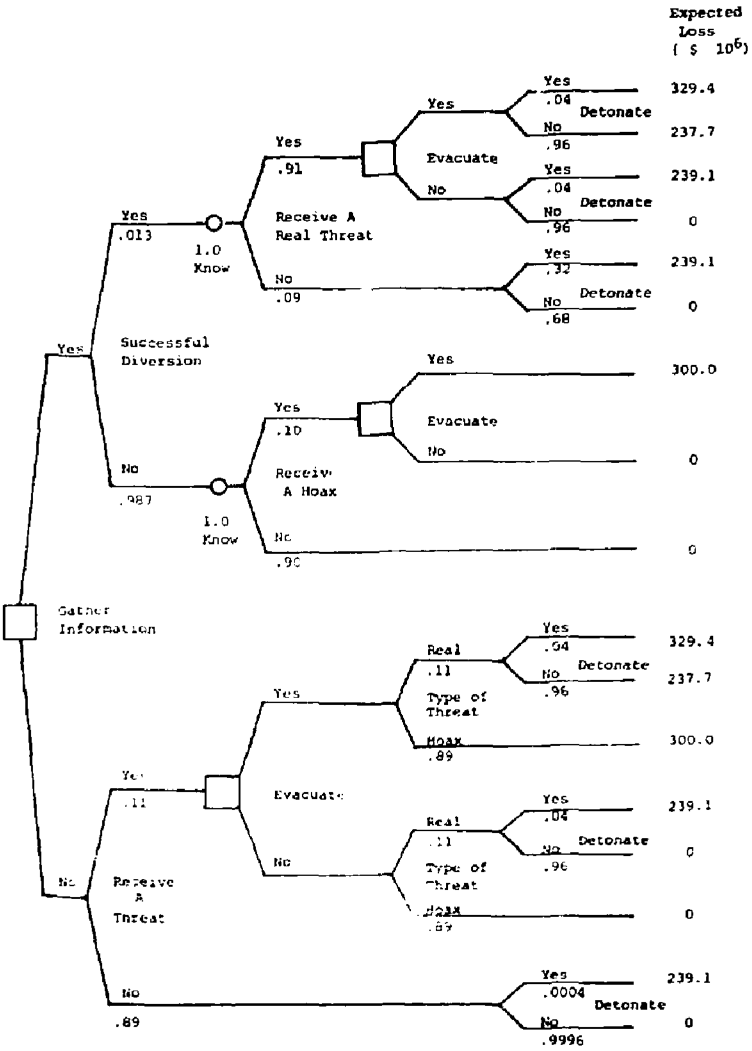


Figure 3.10. Structure for EVPI Calculation

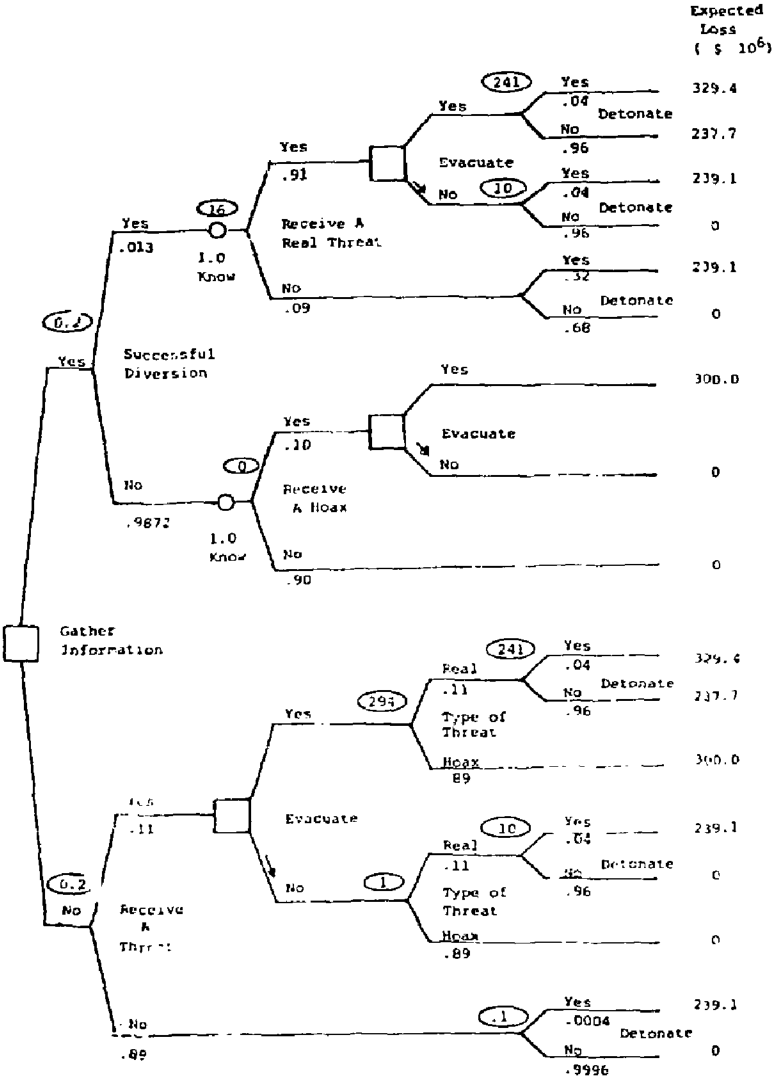


Figure 3.11. Rollback Values for EVPI Calculation

the expected value of the "evacuate" decision would have to exceed the expected value of the "no evacuate" decision by $900 million. This condition would give an expected value of perfect information of about $10 million; however, since the actual information gained is not perfectly reliable, its value would be less.

These calculations are intended primarily to illustrate a structure for quantifying the benefits of an expensive plant shutdown for inventory. They also show the relationship between plant inventories and evacuation -- specifically, how the benefit of the former is determined by the cost of the latter. Before these calculations are carried further, it would be appropriate to review the Consequence Model and the use of expected values as a decision criterion. At that point, the certain equivalent value of the inventory information can be better determined.

IV. SAFEGUARDS TECHNOLOGY MODEL

Simplified Diversion/Consequence Model

To make our discussion of safeguards technology easier, we have simplified the Diversion Model in Figure 2.2. The "pruned" version of the tree is shown in Figure 4.1.

Figure 2.6 shows that Sequences 1, 3, 4, 9, 11, and 12 in Figure 2.2 account for 97 percent of the risk in terms of diverted SNM. The remaining sequences are unlikely; they have low probability of success, and their consequences are no worse than those from Sequences 1, 3, 4, 9, 11, and 12. Because of this stochastic dominance, they have been eliminated from the Six Sequence Diversion Model shown in Figure 4.1. Figure 4.1 will be used to characterize the diversion sequences that our sample MC&A system is designed to detect.

Figure 4.2 shows a diversion model that is simplified even further. Figure 4.2 will be used to combine overall diversion risk and consequence information. The simplifications are in two areas: the diversion model structure and the representation of values in the right-hand column. The main structural change is that Sequences 3, 4, and 9 in Figure 4.1 are represented in Figure 4.2 as a single adversary sequence: employees. This change was made because many of the MC&A systems considered in this chapter influence the probability of diversion for the three adversary sequences 3, 4, and 9.

One minor change to the structure of Figure 4.1 that is reflected in Figure 4.2 is the elimination of the "Quantity per Attempt" node. The uncertainty as to target amount is reflected instead in the "Quantity Diverted" node. The two representations are probabilistically equivalent. The probabilities of all events in Figure 4.2 are computed from Figure 4.1.

The probabilities of interrupting Sequence 1 (P_I) and of detecting Sequence 3, 4, or 9 (P_D) are specified as variables in Figure 4.2. These

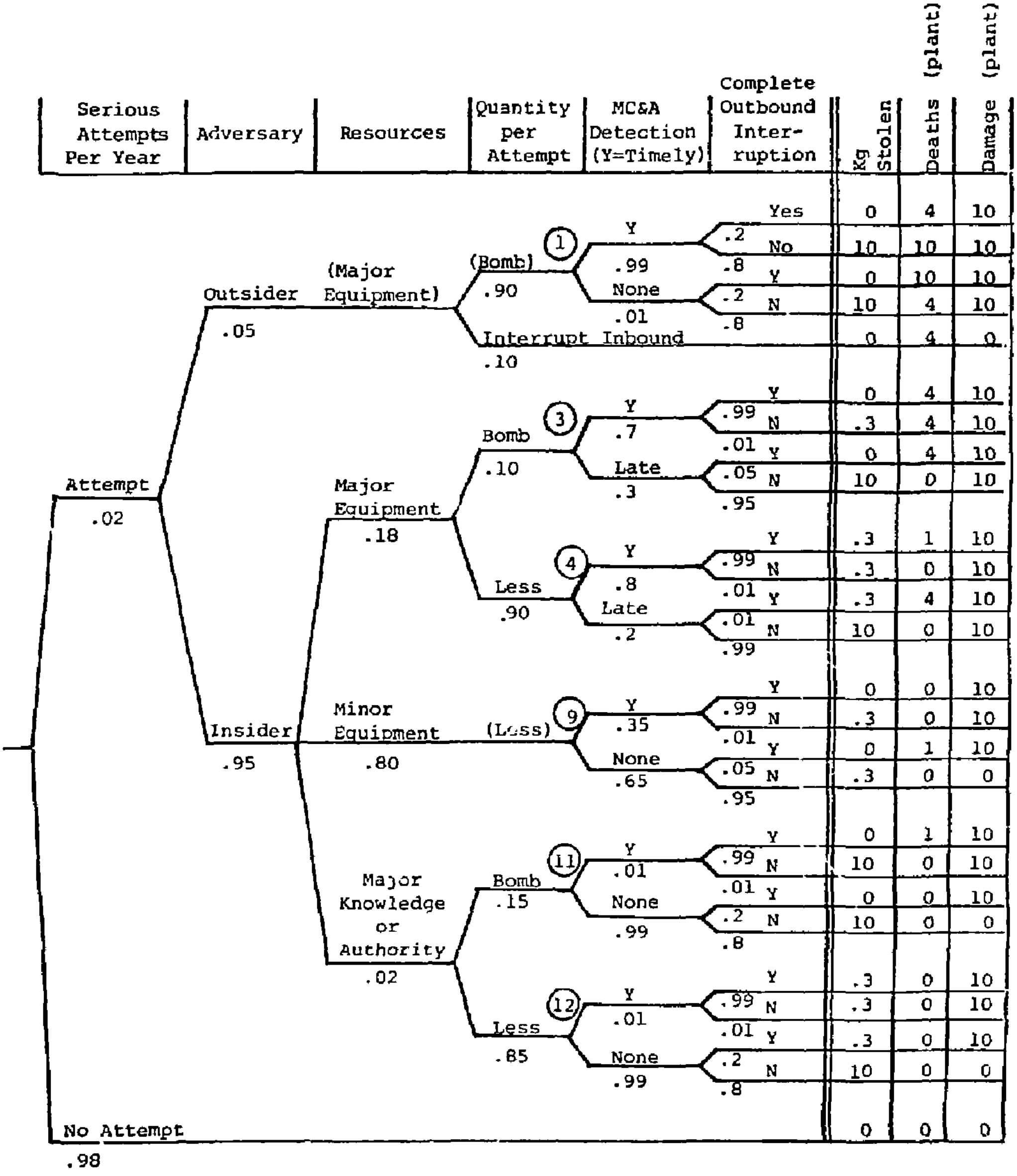


Figure 4.1. Six Sequence Diversion Model

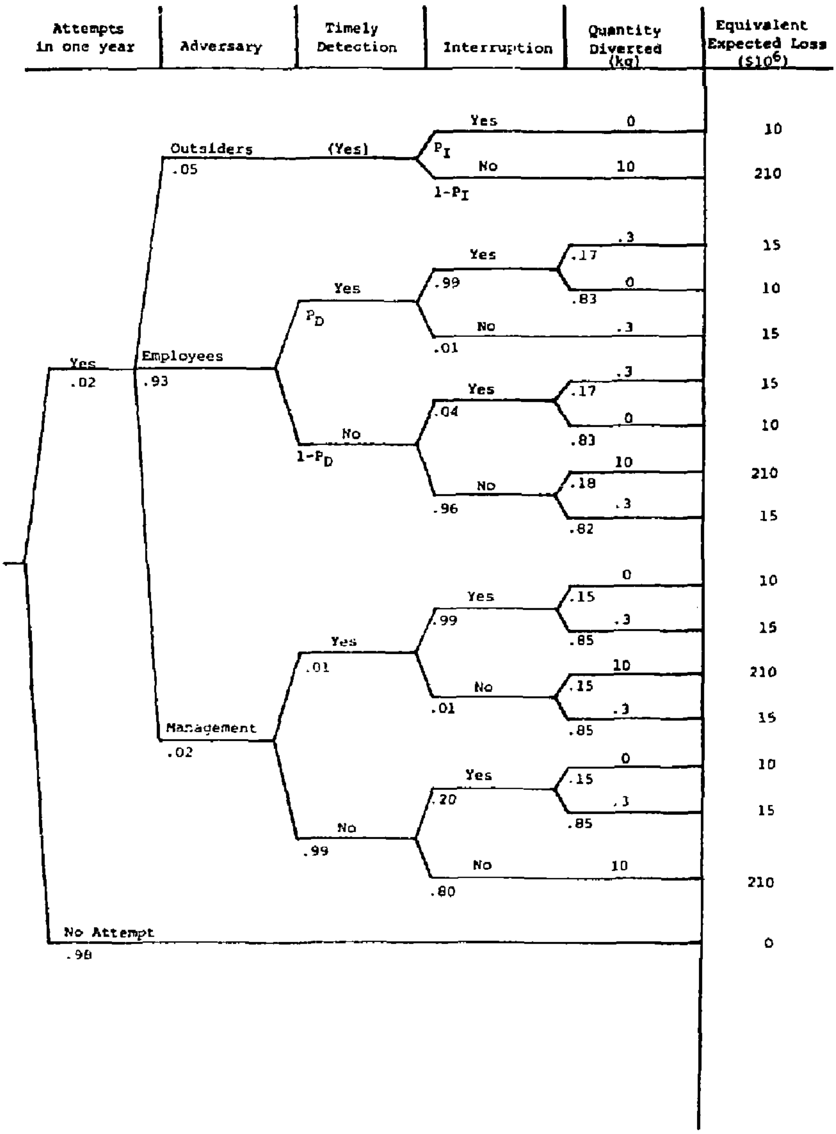


Figure 4.2. Three Sequence Diversion Model

are the variables for which criteria will be established. For the Six Sequence Diversion Model:

$$P_I = .028$$

$$P_D = 0.43.$$

The expected diversion cost C_D is computed from Figure 4.2 by the rollback procedure explained earlier. As a function of P_I and P_D, the resulting equation is:

$$C_D = (1.2 - .7P_D - .2P_I) \ \$\text{million}.$$

Using the base case values of P_I and P_D above,

$$C_D = 1.2 - .30 - .06 \qquad \$840{,}000.$$

This result is 50 percent higher than the $560,000 equivalent loss discussed in Chapter 3. The difference results from the simplification process; it is unimportant for the following discussions.

MC&A System Characteristics

We have developed a simple model of the effectiveness of safeguards system components; the models inputs, algorithms, and results will be described in this section. This model demonstrates a technique for determining overall system performance based on component performance data. It also provides cost data necessary for balancing safeguards system costs and benefits. Our discussion of the model is divided into two parts: MC&A components and physical security components.

Figure 4.3 lists 17 different MC&A components. These are described in a report by General Electric (GE) [6]. The numbers in Column 2 of Figure 4.3 correspond to component numbers in the GE report. Most of these components are included in the LLL test bed design, as indicated in the third column.

General Electric provided capital costs and operating costs for each component, with the exception of numbers 45 and 46. These costs were combined into a single annual cost using a fixed charge rate of 20 percent:

Group Component	GE #	In Test Bed	**	Cost $1,000/year	Probability of Detecting an Attempt (No Tampering) in:			Notes
					Seq. 3	Seq. 4	Seq. 9	
Physical Barriers								
Glove Boxes	26	✓	✓	30	.3 e	.1 e	.1	
Surveillance								
Multiperson Rule	42	✓	✓	500	.9 e	.6 e	.5 e	
Closed Circuit TV	43	✓		300	.1	.01	.01	
Roving Guards	45			375	.3	.1	.1	
Guards at Vault	46			150	.3	.1	.1	
Monitoring Zones								
Personnel Detectors	49	✓		50	.1	.1	.1	- 4 same as 3 because of multiple attempts
Radiation Detectors	50	✓	✓	65	.7 e	.1	.05	
Material Location Monitoring								
Physical Search	68			100	.9 e	.7 e	.2 e	- Assumed not acceptable to employees
Noncontact Search	69	✓		65	.6 e	.1	.05	
Sampler Monitor	75	✓	✓	40	.1 e	.3	.1	- Unlikely to be used in Sequence 3
Transfer Monitor	83	✓		40	.4	.01	.005	
Event Detection	84	✓		10	.4 e	.01 e	.005 e	- Not independent of #75
Transfer Quantity Monitor	86	✓		150	.4	.01	.005	
Control Access to SNM								
Double Wall Pipe	93	✓	✓	10	.4 e	.3 e	.1 e	- Unlikely to be used in Sequence 9
SNM Inventory Measurement								
Volume Monitor	99	✓		300	.3	.01	.005	- Adversary could temporarily invalidate system
Storage Monitor	111	✓		250	.5	.1	.05	
Real-time Accounting	140	✓		1,900	.4	.1	.05	

e = efficient points, i.e., the set of components such that no other component has a higher detection probability for the same or lower component cost.

** = effective in combination

Figure 4.3. Effectiveness of Various MC&A Components

$$\begin{pmatrix}\text{Annual}\\ \text{Cost}\end{pmatrix} = 0.2\times\begin{pmatrix}\text{Capital}\\ \text{Cost}\end{pmatrix} + \begin{pmatrix}\text{Operating}\\ \text{Cost}\end{pmatrix} .$$

A fixed charge rate is the average annual cost to an organization to support a capital investment of $1, including interest, depreciation, and tax effects. Annual charges are shown in Figure 4.3. The LLL project team supplied cost estimates for systems 45 and 46, assuming 15 employee-years per year (5 guards/shift; 3 shifts) required for system 45 and 6 for system 46. A cost of $25,000 per employee-year was also assumed.

Component performance is measured in terms of the probability of detecting an insider attempting covertly to divert SNM. These probabilities were assigned subjectively by the LLL project team. Since these components all can detect Sequences 3, 4, and 9, assessments were made for each sequence. However, the components were considered not to be effective against Sequences 1, 11, or 12. Results are shown in three columns in Figure 4.3. The numbers in these columns are the probabilities that the adversary sequence listed at the head of the column will be detected by the particular device if installed in the MC&A system. This subjective assessment requires the analyst to take several events into account, as shown in Figure 4.4a. The adversary must first take actions that the safeguards component is designed to detect. Next, the component must be operational; for instance, it must not be disabled for inspection. Third, the analyst considers whether or not the adversary is detected; occurs; detection includes notification of the guards.

In Figure 4.4a, it is assumed that the adversary has not tampered with the particular MC&A component in question. The possibility is also excluded that an attempt is made by an adversary who knows a particular component is down and who chooses that time to make an attempt. However, because it is likely that a successful diversion would involve tampering, a second assessment was made using the events in Figure 4.4b. The probability of detection in the "tampering" case is the sum of the joint probabilities of the two events leading to detection in Figure 4.4b. These events were considered implicitly by the person giving the detection probabilities in Figure 4.3.

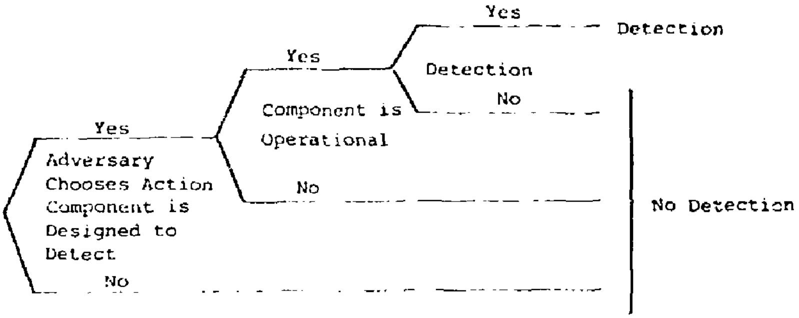


Figure 4.4a Events Considered in Assigning Detection Probabilities

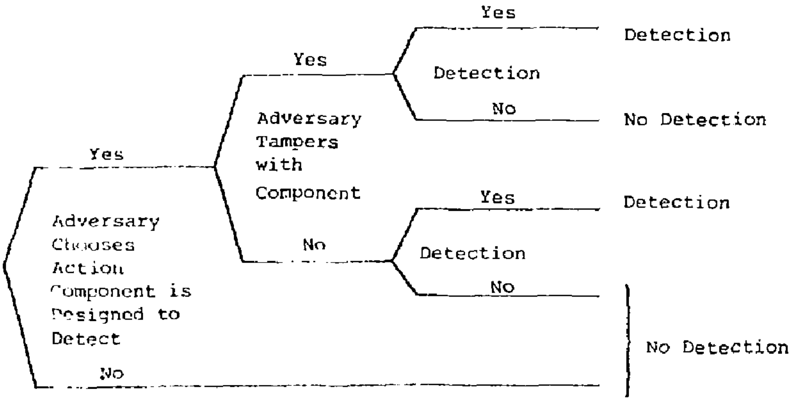


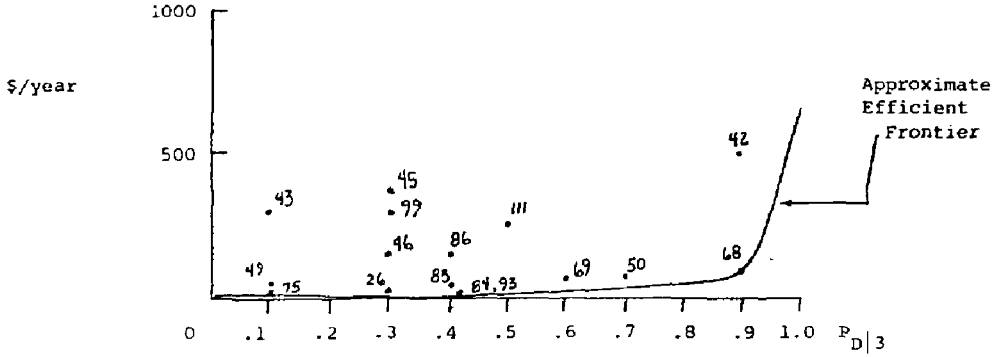
Figure 4.4b Tampering Consideration in Assigning Detection Probabilities

Calculation of the overall probability of detection for a large system is a complex problem -- one that is addressed explicitly but not yet fully solved by the sophisticated computer software being developed at LLL. In order to provide quantitative input for our example, we first restricted the size of the MC&A system considerably. We did this by identifying components that achieve a given level of performance (detection probability) for the least cost. Each component's cost and performance was plotted in Figure 4.5. The set of least-cost components was identified by drawing the efficient frontier for each sequence. That is, for each component cost the point with the highest detection probability. Components on the frontier are denoted with an "e" in the probability columns in Figure 4.3. These results produce only a first-cut estimate of the set of most efficient safeguards components, since only "non-tampering" probability assessments were used and since combinations of components to form systems were not included in the selection process. The following components were on the efficient frontier in at least one sequence:

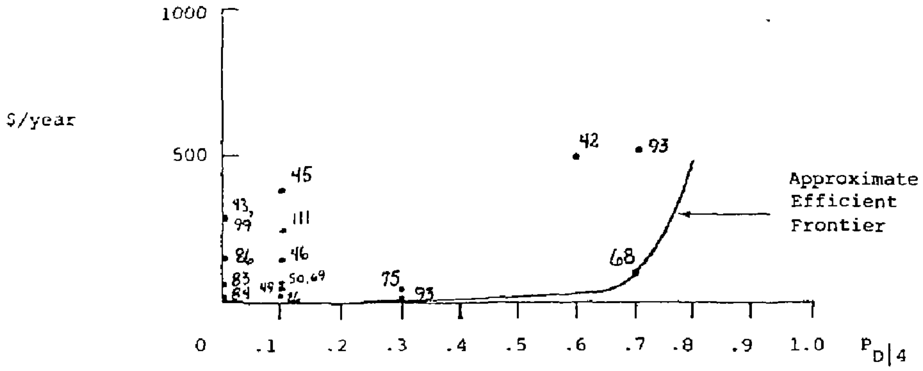
System	Disposition
26 Glove Boxes	Selected for further analysis
42 Multiperson Rule	" " " "
50 Radiation Detectors	" " " "
68 Physical Search	Dropped because total cost assumed to be significantly higher than GE estimate (which excluded employee morale costs)
69 Noncontact Search	Dropped because of similarity to #50
75 Sampler Monitor	Selected for further analysis
84 Event Detection	Dropped in favor of #75; not independent of #75
93 Double Wall Pipe	Selected for further analysis·

Thus, five safeguards components were selected for the example. Probabilities of detection in case of tampering and no-tampering were assigned to each; the probabilities are shown in Figure 4.6.

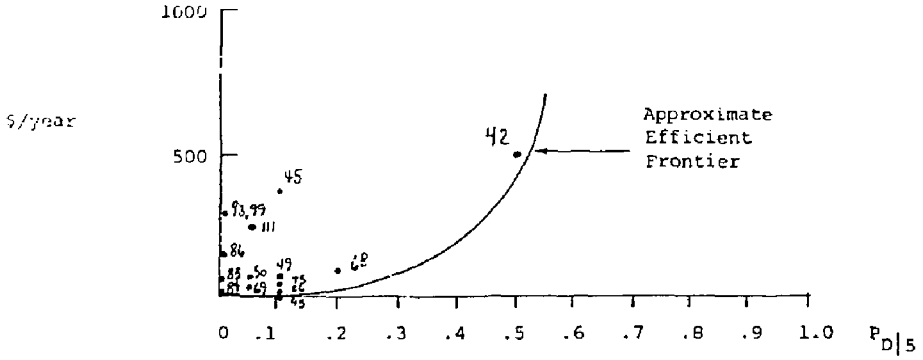
Each of the five components (numbers 26, 42, 50, 75, and 93) has a nonzero probability of detecting an adversary in Sequence 3, 4, or 9. Also, the components may be used in combination to increase the likelihood



Sequence 3--One Attempt: Major Resources



Sequence 4--Multiple Attempt: Major Resources



Sequence 9--Minor Resources

Figure 4.5. MC&A Component Cost and Performance

GE Number	Component	Cost ($1000/year)	Probability of Detection (Tampering Case/No-tampering Case) Sequence: 3	4	9
26	Glove Boxes	30	.10/.30	.10/.10	.01/110
42	Multiperson Rule	500	.45/.90	.30/.60	.20/.50
50	Portal radiation detectors	65	.35/.70	.10/.10	.05/.05
75	Sampler Monitor	40	.10/.10	.30/.30	.10/.10
93	Double Wall Pipe	10	.05/.40	.05/.30	.05/.10

Figure 4.6. Characteristics of MC&A Components Selected for Example

of detection. Therefore, a simple probabilistic model of system effectiveness was constructed to compute the cost of possible combinations of components and the overall probability of detecting an employee attempt (Sequences 3, 4, and 9). The algorithm for this calculation is given in Figure 4.7 and the results are shown in Figure 4.8.

The key assumption in the algorithm is that probabilities of detecting a given adversary by the individual components are independent of detection by other components. This assumption seems reasonable for the five components used to produce Figure 4.8.

In the left-hand column of Figure 4.8, a number between 1 and 31 is assigned to each combination of safeguards components. Thus, there are 31 different safeguards system designs, each to be evaluated according to price and performance. The second column shows the system cost, which is the sum of individual component costs. Column three gives the probability of detecting an employee adversary; this parameter is P_D in Figure 4.2. The last column lists the components of the MC&A system design included in each system.

Figure 4.8 provides some basic information by which the MC&A components in the 31 different system configurations can be evaluated. The evaluation methodology we have used will designate the least-cost combination of MC&A components to achieve each level of performance (probability of detection). The evaluation begins by plotting each of the 31 system designs in Figure 4.8. This curve is shown in Figure 4.9. The abscissa in Figure 4.9 corresponds to the performance of the system; the ordinate measures the cost. The curve in the figure is the efficient frontier for the 31 system designs. It indicates the minimum cost of achieving each level of performance. We assume this curve represents the "economics" of material control -- i.e., the total cost of MC&A safeguards possible at a reprocessing plant. The function

$$C_{MC\&A} = (6.8 \cdot 10^{-3}) e^{11 \cdot P_D} \text{ (\$million/year)}$$

approximates this curve and is shown as the dotted line in Figure 4.9.

i = Index of a sequence

j = Index of an MC&A component

I = Set of all sequences where adversary is an employee

J = Set of all installed MC&A components

$\{s=i\}$ = Probability of sequence i

$\{d_j|s=i\}$ = Probability of component j detecting an adversary in sequence i (assume tampering is possible)

$\{d_k, d_j|s=i\}$ = Probability of both components j and k detecting sequence i

$\{d_k, d_j|s=i\} = \{d_k|s=i\}\{d_j|s=i\}, \quad k \neq j$

(i.e. components j and k are probabilistically independant)

D = Event of detection by one or more MC&A components

COMBINING COMPONENTS

$$\{D|s=i\} = 1.0 - \prod_{j \in J} (1.0 - \{d_j|s=i\})$$

COMBINING SEQUENCES

$$\{D\} = \sum_{j \in I} \{D|s=i\}\{s=i\}$$

COST OF SYSTEM

c_j = Cost of MC&A component j

C = Cost of total MC&A system

$$C = \sum_{j \in J} c_j$$

Figure 4.7. Algorithm for Aggregating MC&A System Cost and Performance

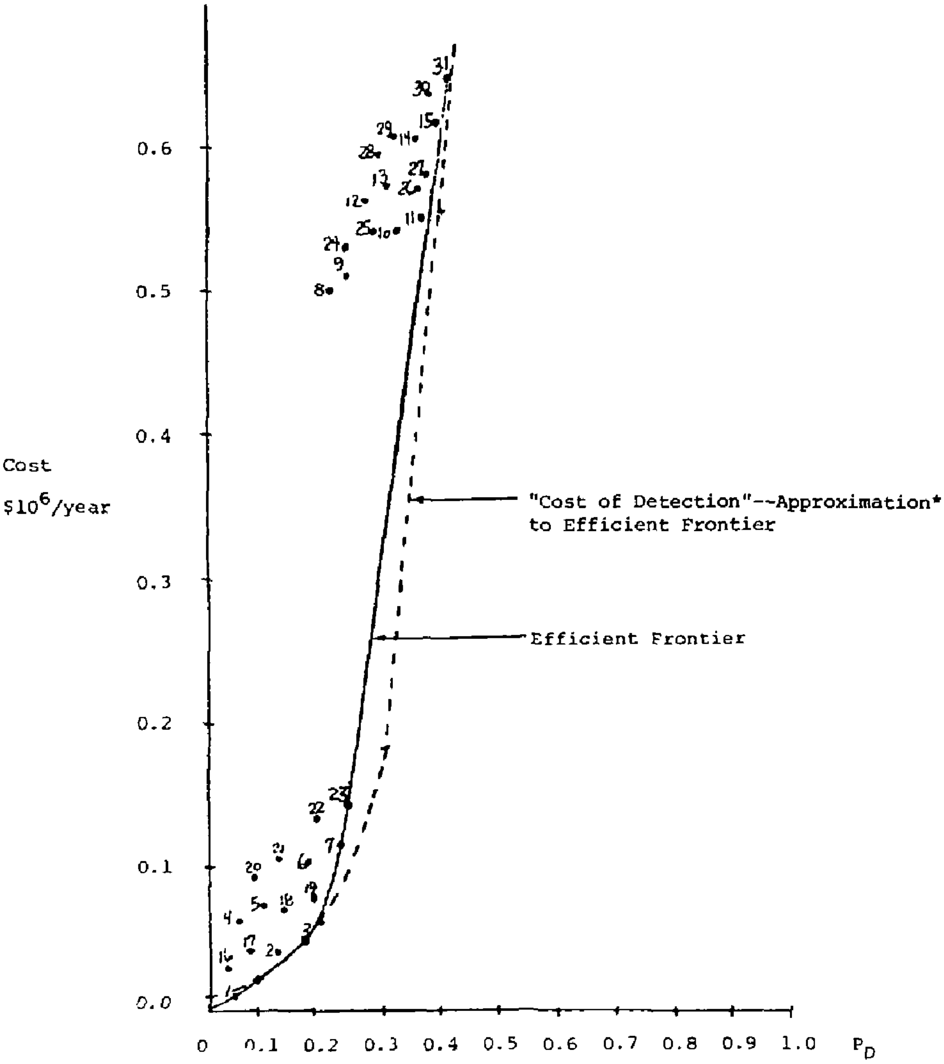
```
SYSTEM       *       **                                         ***
NUMBER     COST     PROB    COMPONENTS INCLUDED (GE Number)

   0          0     0.
   1         10     .05     93
   2         40     .13     75
   3         50     .18     75 93
   4         65     .06     50
   5         75     .11     50 93
   6        105     .19     50 75
   7        115     .23     50 75 93
   8        500     .22     42
   9        510     .26     42 93
  10        540     .32     42 75
  11        550     .36     42 75 93
  12        565     .27     42 50
  13        575     .31     42 50 93
  14        605     .36     42 50 75
  15        615     .39     42 50 75 93
  16         30     .03     26
  17         40     .08     26 93
  18         70     .15     26 75
  19         80     .20     26 75 93
  20         95     .09     26 50
  21        105     .13     26 50 93
  22        135     .21     26 50 75
  23        145     .25     26 50 75 93
  24        530     .24     26 42
  25        540     .28     26 42 93
  26        570     .34     26 42 75
  27        580     .37     26 42 75 93
  28        595     .29     26 42 50
  29        605     .32     26 42 50 93
  30        635     .39     26 42 50 75
  31        645     .41     26 42 50 75 93
```

* cost in $1000/year

** PROB = P_D = Probability of detecting an adversary who is an employee

*** GE Number: see Figure 4.6 for identification

Figure 4.8 Output from Systems Effectiveness Model



P_D = Probability of Detection

Note: See Figure 4.8 for key to system numbers

$*C_D = 6.8\ 10^3\ e^{11\ P_D}$ ($million/year)

Figure 4.9 MC&A System Performance Against an Employee

The distinct grouping of points in Figure 4.9 is caused by component 42, the multiperson rule. This component is relatively expensive and effective, so systems that include it are above and to the right of systems that exclude it. In considering additional MC&A components, including variations on component 42, one would "fill in" the curve in Figure 4.9.

Physical Security Characteristics

Figure 4.10 gives information to that in Figure 4.6, in this case for physical security components. From this list, three systems were selected:

Component (GE number)	Name
10	Enclosed access route
12	Isolation barriers for access route
35	Remotely-activated barriers for critical zones.

GE system 45 was excluded because of cost; systems 58, 59, and 60 were assumed to violate occupational safety requirements. The selected components are assumed to protect against Sequence 1. Figure 4.11 plots the total cost and effectiveness of these components. We assume these systems represent incremental improvements to existing physical security, since none of them are included in the design of the test bed. This assumption is in contrast to the 31 MC&A system designs, which are assumed to comprise the total MC&A system. Further, we assume the elements of physical security not shown in Figure 4.10 but included in the test bed design are cost-effective; i.e., their marginal benefit in terms of increased security exceeds their marginal costs.

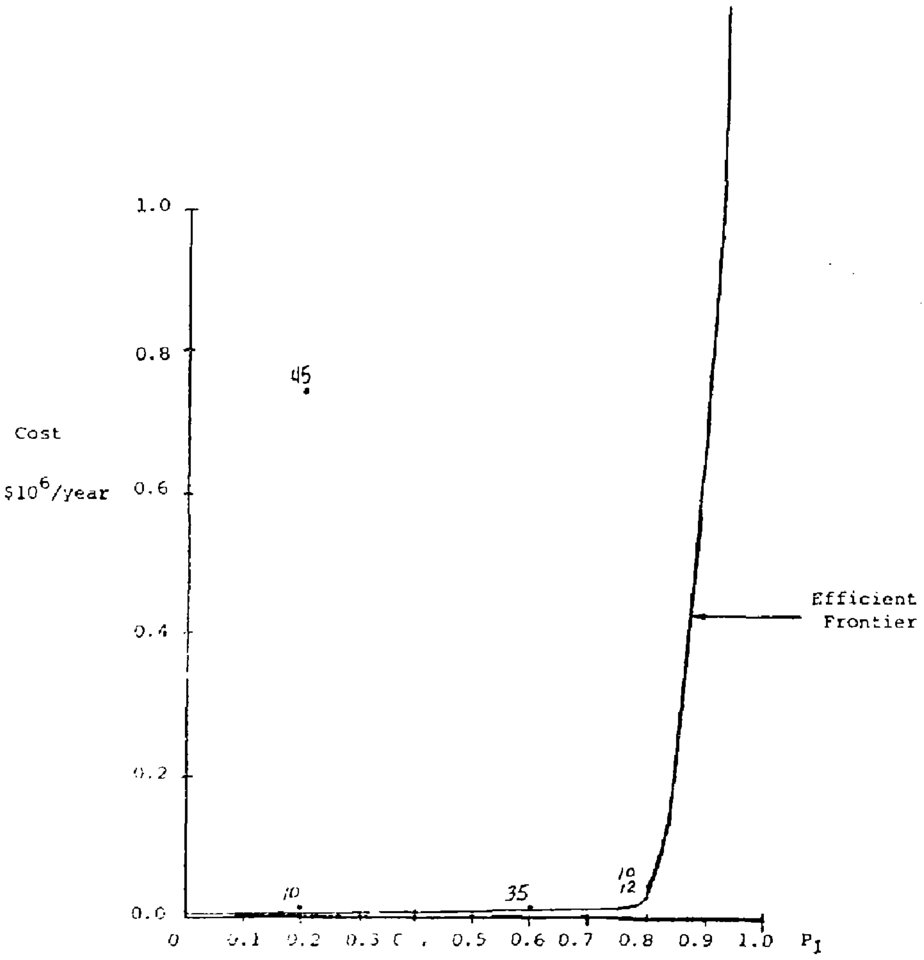
An efficient frontier is drawn in Figure 4.11. Its shape in the region $P_I = .8$ to 1.0 is assumed, since none of the physical security systems performed in that range. The cost curve for physical security is assumed to be:

$$C_{PS} = (1.2 \cdot 10^{-10}) e^{25 \cdot P_I} \text{ (\$million/year)}.$$

This equation approximates the efficient frontier in Figure 4.11.

GE Number	Component	Cost ($1000/year)	Probability of Interrupting Outside Attempt	Note
10	Enclosed Access Route	20	.2	
12	Access Route Isolation Barriers	10	.8	When combined with 10.
35	Remotely Activated Zone Isolation Barriers	10	.6	
45	Roving Guards	750	.2	LLL estimate of cost to double guard force. Not used for example.
58, 59, 60	Diverter Debilitation Systems	55-100	$\leq$ .8	Not used; assumed prohibited for occupational safety reasons.

Figure 4.10. Characteristics of Physical Security Components



P_I = Probability of Interrupting an Outside Attempt

Note: See Figure 4.10 for key to component numbers

Figure 4.11. Physical Security Performance

V. ANALYSIS OF RISK CRITERIA

Marginal Evaluation of MC&A Criteria

This chapter describes a methodology for judging the appropriate level of safeguards performance. We will use the evaluation framework described in Chapter 2, and the Diversion, Consequence, and Technology models described in Chapters 2, 3, and 4. We first discuss setting criteria for MC&A system performance against an employee adversary. This task is roughly equivalent to choosing a level for P_D in Figure 4.2. We assume that physical security and safeguards against diversion by plant management are set at a nominal level. Because we are choosing the criteria for P_D, while other things are constant, we refer to this as a "marginal" evaluation. Following the marginal evaluation, we shall describe a joint optimization of MC&A and physical security.

In Figure 5.1, which is the same as Figure 1.1, we show the tradeoff between MC&A cost and diversion risk. As the probability of detecting an attempt increases from 0 to 1, the risk from diverted SNM drops. In Figure 5.1, the diversion cost is the expected value of the probability tree in Figure 4.2, with P_I set at its nominal value, .7. Since the expected value of diversion consequences is linear in the detection probability P_D, the diversion cost is a straight line. However, if $P_D = 0$ (i.e., there was no way to detect attempts), the frequency of attempts might be higher, causing the diversion risk to rise sharply at the left of Figure 5.1. We have not explicitly modeled that case, so the diversion cost curve is not shown for $P_D < .1$.

On the same graph we show the cost of achieving each detection probability. This "Safeguards Cost" is taken directly from Figure 4.8.

The sum of the safeguards and diversion costs curves is the U-shaped total cost. It has a minimum at $P_D = 0.2$. Increasing P_D beyond .2 creates a cost that exceeds the resulting drop in diversion cost. If P_D were less than 0.2, the costs of improving safeguards would be small relative to the benefits. Thus, there is an incentive to shift toward $P_D = 0.2$ from

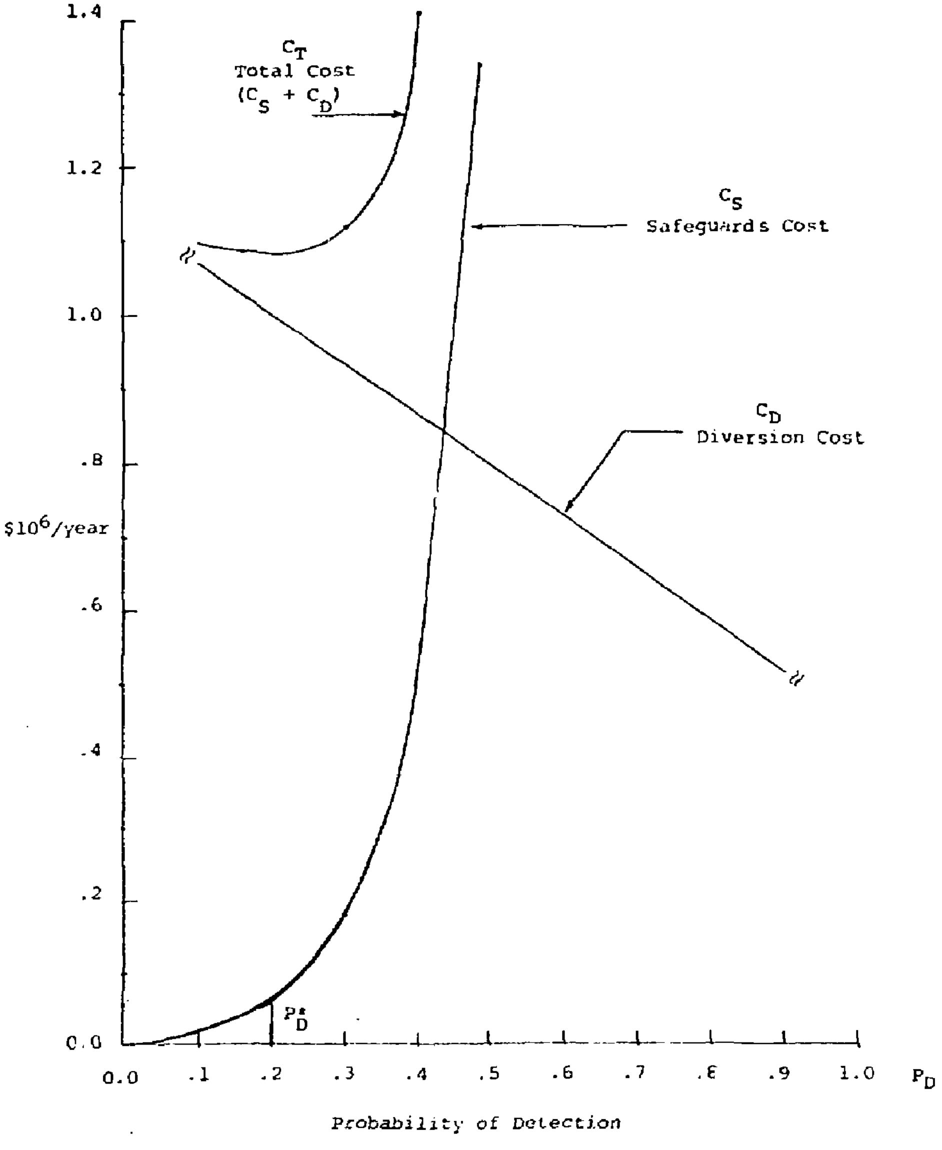


Figure 5.1. Evaluation of MC&A System Performance

either side. Further, the total cost curve is relatively flat in the range $.1 \leq P_D \leq .3$. This fact indicates something about the needed precision for determining P_D in that range.

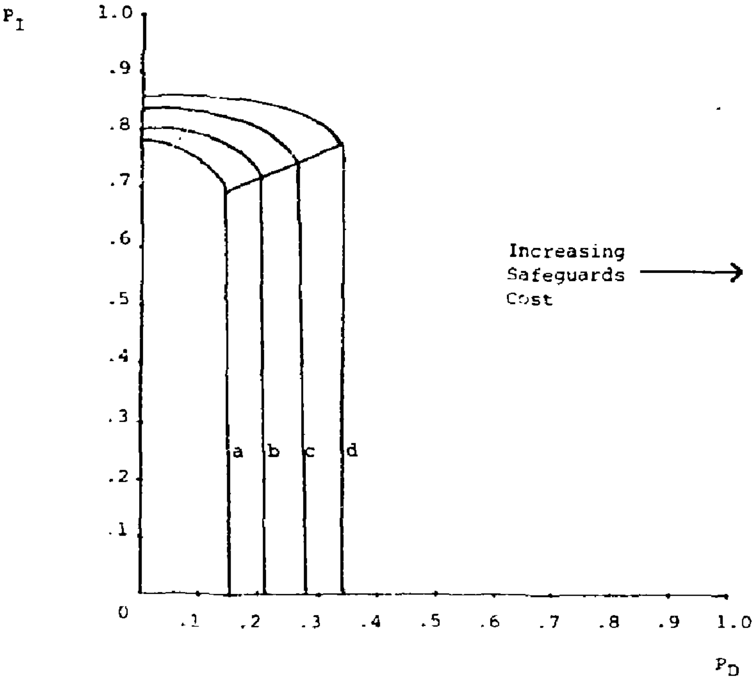
Joint Safeguards Decisions -- MC&A and Physical Security

The marginal analysis in Figure 5.1 demonstrates the optimization process. However, MC&A decisions should be considered in light of other safeguards decisions such as those that concern physical security. These two factors are interdependent in that they should be "balanced" -- i.e., one should not be a weak link relative to the other. Discussion of this joint decision analysis process will also demonstrate the tradeoffs between strengthening physical security versus MC&A.

This optimization, as before, requires information about quantitative safeguards and diversion cost. The graph in Figure 5.2 shows safeguards costs. The axes are the two decision variables P_D and P_I. The optimal settings for these variables will be P_D^* and P_I^*. The curves represent equal safeguards costs for P_I and P_D; for instance, the outermost curve shows the locus of P_I, P_D points that have combined annual cost of $294,000. The outer curve's shape indicates that once a value for P_D^* is chosen, the cost of moving P_I from 0 to .7 adds little to the total cost. Moving up and to the right (giving better system performance) increases system costs. The shape of the curves gives policy-makers insight into the tradeoff between increasing MC&A and physical security. In this case, physical protection is inexpensive relative to MC&A costs.

Similarly, Figure 5.3 shows lines of equal diversion cost. Curve "D" corresponds to the base case data in Figure 4.2. The other curves will be used for sensitivity analysis. The diversion "iso-cost curves" are straight lines because diversion cost is linear in P_D and P_I. Safeguards costs are assumed to be exponential functions of P_I and P_D.

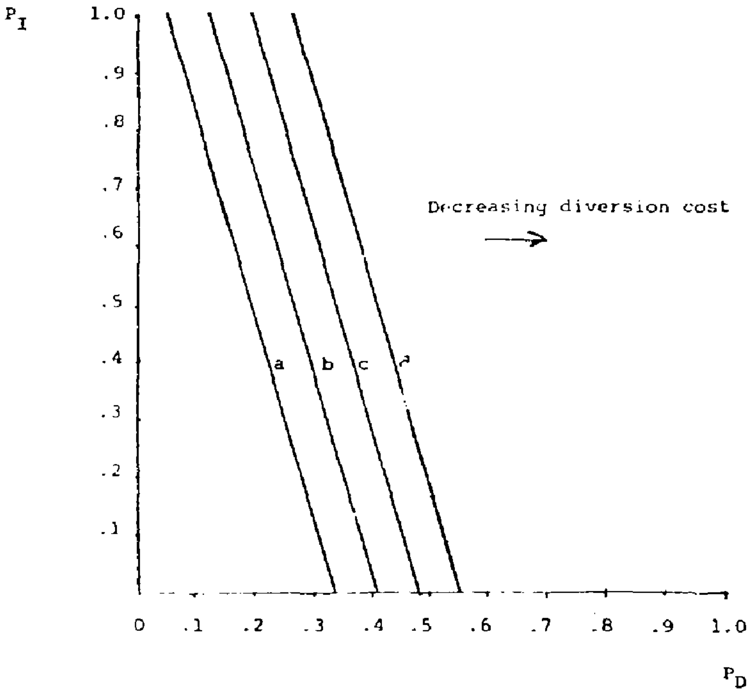
Safeguards costs increase when P_I and P_D increase, while diversion risks decrease. This fact implies a minimum total cost point, similar to the minimum in Figure 5.1.



Curve represents contour of constant safeguard system cost.

Curve	System Cost ($\$10^6$/year)
a	.04
b	.07
c	.14
d	.29

Figure 5.2. Safeguards System Cost Curves



Curve	Diversion Cost C_D (\$$10^6$/year)
a	.96
b	.91
c	.86
d	.81

Figure 5.3. Diversion Cost Curves

Overlaying Figures 5.2 and 5.3 produces the graph in Figure 5.4. The points of tangency between safeguards cost and diversion cost represent minimum cost points relative to horizontal or vertical shifts on the graph. These points of tangency are labeled "a", "b", "c". and "d". The total cost and other information for the four cases is indicated at the bottom of Figure 5.4. For the base case (point "b"):

C_D = \$910,000

C_S = \$ 70,000

P_I^* = .72

P_D^* = .20.

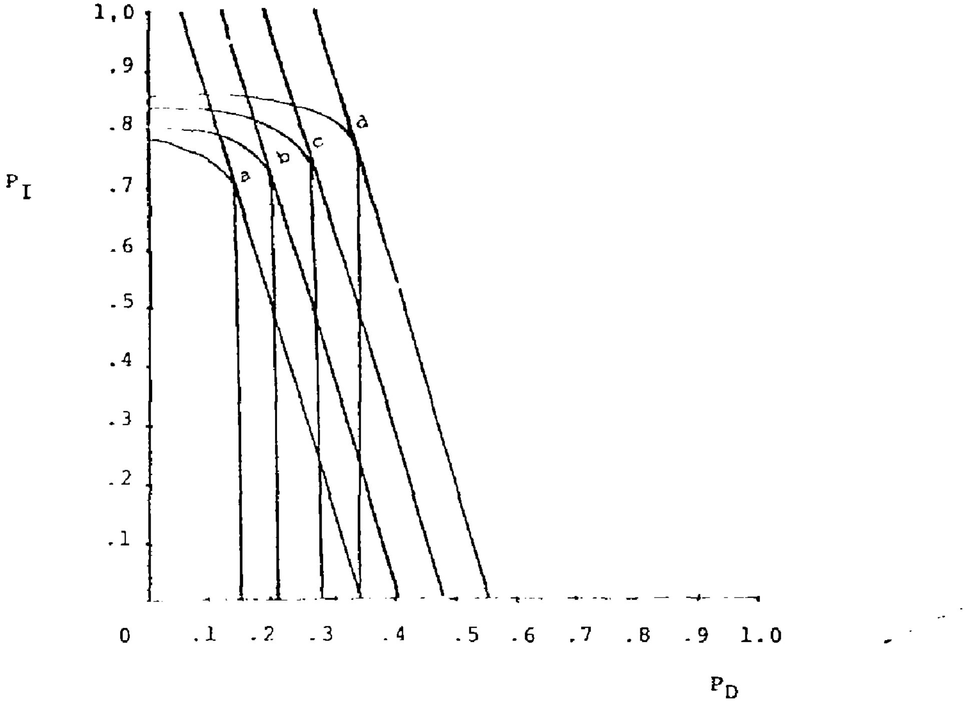
The total cost at point "b" is \$980,000. Notice that this cost is lower than the total cost at points "a", "b", "c", or "d."

As diversion cost C_D decreases, the safeguards cost C_S increases. This fact can be seen by looking at the rows labeled C_D and C_S at the bottom of Figure 5.4. This phenomenon is plotted in Figure 5.5, which shows the cost C_S of an optimal safeguards system to attain a range of diversion risks C_D. The base case set of C_S and C_D occurs when the curve is tangent to a straight line with slope = -1.

Figure 5.5 is in some sense the most highly-aggregated output from the analysis. It shows a major policy-maker the cost of reducing risks to various levels, suppressing all detail on how the costs and risks are computed and optimized. It also conveys the fact that risks cannot be made arbitrarily low without significantly increasing cost. It should also be noted that this solution is an approximation because this value was derived using the continuous approximation to the efficient frontier in Figure 4.9. It could be that there is no system having the discrete cost, C_D and the detection probability P_D^*. However, in a less aggregated model it may be possible to produce the desired systems by incrementing safeguards in varying degrees.

Sensitivity Analysis

The highly aggregated models behind this analysis have several key



Point:	a	b	c	d	
C_T	1.00	.98	1.00	1.10	Total Cost = $C_S + C_D$ ($\$10^6$/year)
C_D	.96	.91	.86	.81	Diversion Cost ($\$10^6$/year)
C_S	.04	.07	.14	.29	Safeguard Cost ($\$10^6$/year)
P_D^*/P_I^*	.14/.69	.20/.72	.27/.75	.33/.78	Optimal Setting of P_D and P_I
C_{m_c}	.032	.064	.128	.256	MC&A System Cost ($\$10^6$/year)
C_{ps}	.004	.008	.016	.032	Physical Security Cost ($\$10^6$/year)

Figure 5.4. Optimal Setting of P_D and P_I for Four Cases

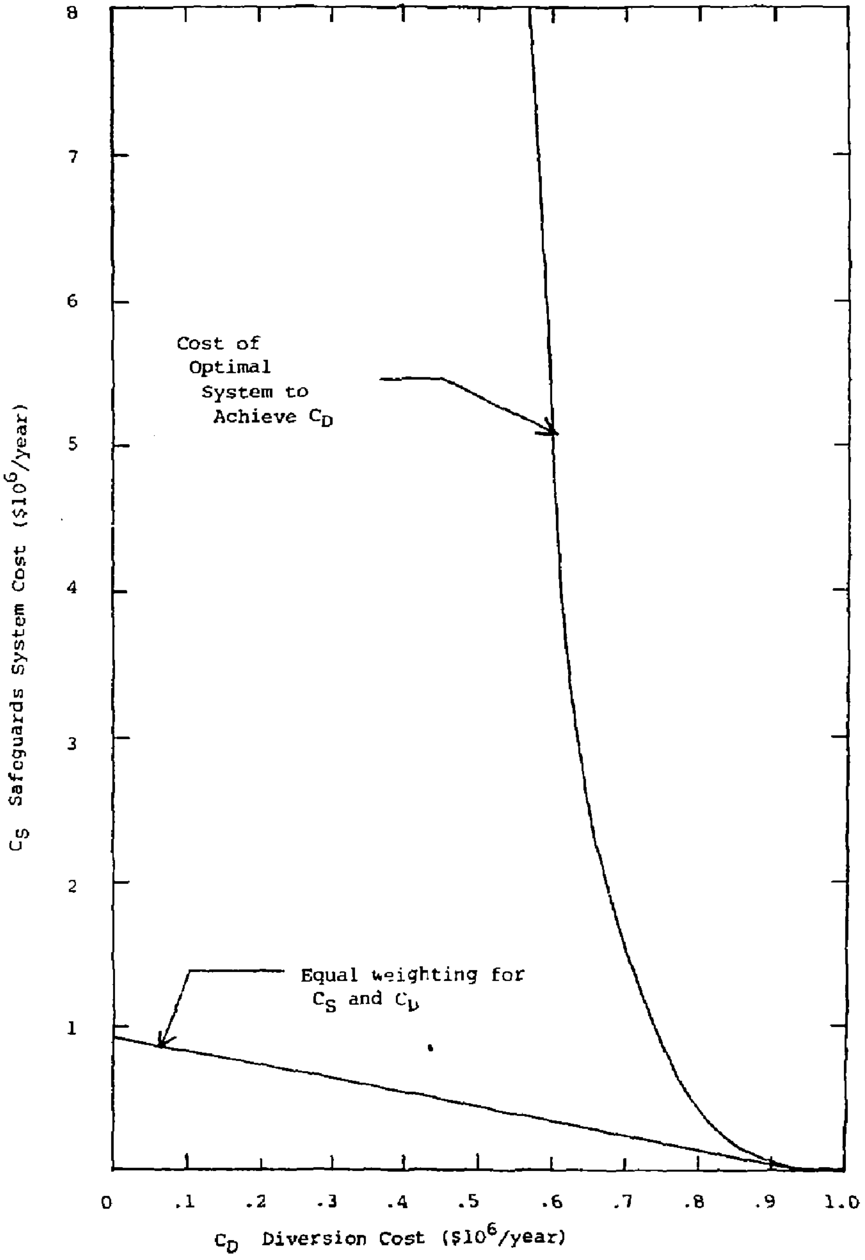


Figure 5.5. Tradeoff Between Diversion Risk and Safeguards Cost

parameters. Figure 5.6 shows how the decision on MC&A criteria (P_D^* -- one of the two decisions being considered) changes with variations in these key parameters:

- P_A (probability of attempt)
- V_D (tradeoff value assigned to each death)
- P_W (probability that an adversary could construct a working bomb from 10 kg of SNM).

The base case is: $P_A = 0.02$; $V_D = \$10^6$; and $P_W = 0.05$. A fourth parameter λ is the relative weighting of safeguards costs and diversion costs. It also corresponds to the negative slope of the straight line in Figure 5.5.

An important insight to be gained from Figure 5.6 is that the decision on MC&A system performance P_D^* does not change significantly as these key parameters are varied. The reason for this condition is that additional safeguards are <u>assumed</u> to be expensive and only marginally effective. This assumption, which is based on the analysis in Chapter 4, deserves careful scrutiny.

The Decision to Reprocess Commercial Reactor Fuel

The preceding section dealt with the decision on how safe to make the reprocessing plant. That decision depends on the costs of alternatives to reduce the risk -- for instance, improving physical security or the MC&A system. At the conclusion of the plant optimization and criteria-setting process, the facility is "optimized" in terms of cost and safeguards; the risk is as low as it should be, given the decision to reprocess spent fuel.

This section addresses the questions: "Is the optimal design safe enough?" and "Should we build the plant?" The answers depend not on the cost of safeguards, but rather, on the cost of alternatives to reprocessing. The alternative considered here is direct disposal of spent fuel and additional mining of fissile ores to replace the spent nuclear fuel.

In a report for NSF [7], it was found that reprocessing would save slightly less than 0.5 mills/kilowatt-hour (kWh) in average electricity

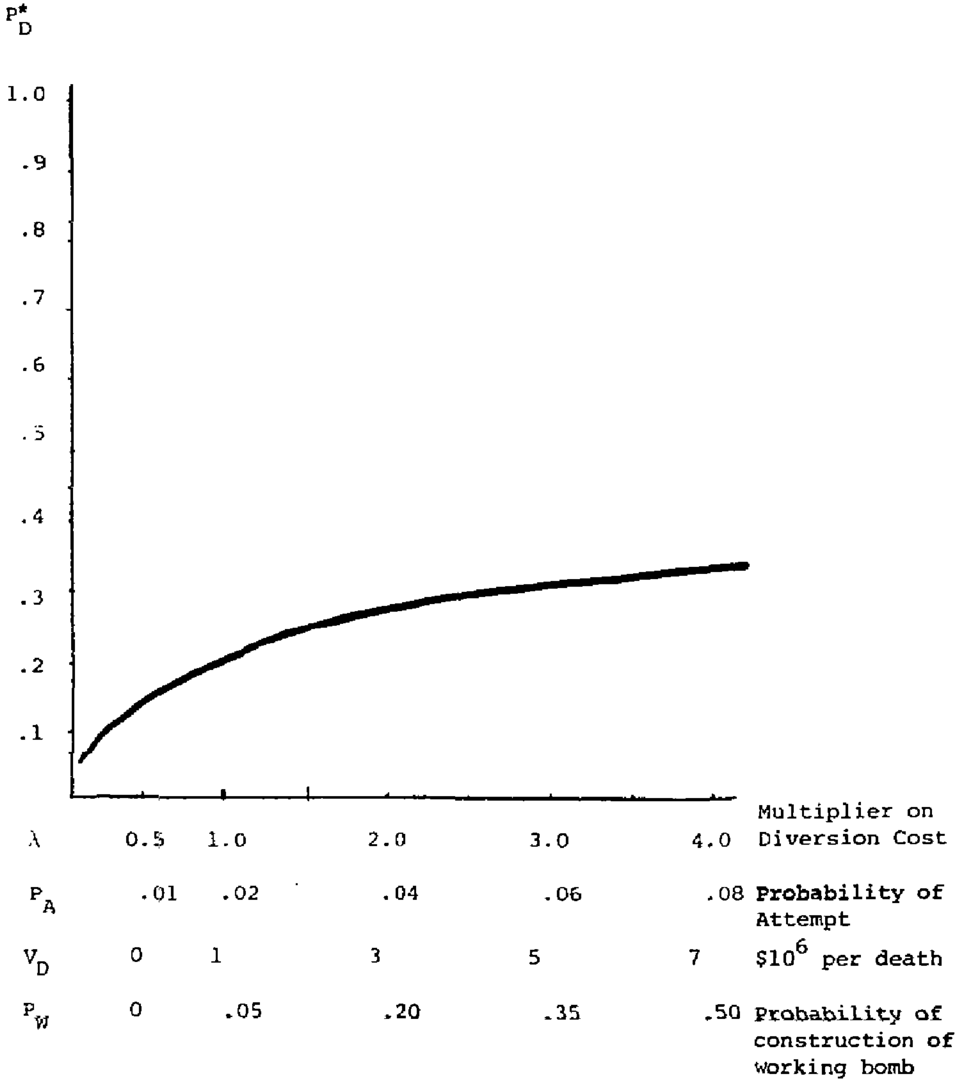


Figure 5.6. Sensitivity Analysis for P_D^*

bills when compared to the alternatives. This saving includes a credit for recovered plutonium and uranium, although the estimates were based on yellowcake valued at \$20/pound (lb). At \$40/lb., which is more representative of today's prices, the relative savings would be close to 1 mill/kWh. The hypothetical plant can reprocess fuel from fifty 1000-megawatt (electric) commercial reactors. If these plants were operating at a 65 percent load factor, the benefits would be:

$$\left(\frac{1 \text{ mill}}{\text{kWh}}\right) (50\cdot.65 \text{ plants}) \cdot \left(\frac{10^6 \text{ kw}}{\text{plant}}\right)\left(8800 \frac{\text{hrs}}{\text{yr}}\right)\left(10^{-3} \frac{\$}{\text{mill}}\right) \sim \$290{,}000{,}000/\text{year}.$$

If it is assumed that all reprocessing costs except the diversion risk are internalized in the 1 mill/kWh savings, then an annual expected risk of less than \$1 million is being compared with a \$290 million expected annual benefit. Further, if the Consequence Model is accepted as a reasonable first estimate of the risk, then a decision to forego \$290 million benefit for a \$560,000 risk exhibits one or all of the following characteristics:

- An extreme level of risk aversion
- Significant other risks (e.g., nuclear proliferation or sabotage) that are not internalized
- Misinformation about the diversion risk
- Inconsistent decisions.

It is, of course, possible that the estimate of the risk could be highly inaccurate. However, the estimate would have to be inaccurate to three orders of magnitude before the risks of diversion would exceed the benefits of reprocessing in terms of expected values.

If these quantitative models are ultimately to be used for weighing the benefits and costs of improved safeguards, and if the risk attitudes revealed by this \$560,000/\$290,000,000 comparison were incorporated in the analysis, then inordinate amounts would be spent for marginal safeguards improvements. If these analytical tools are to be useful to policymakers, the question of consequences and risk attitudes should be carefully examined.

Calculations

Figure 5.7 shows the derivation of equations used to plot the results in the figures in Chapter 5.

FIGURE 5.1 Evaluation of MC&A System Performance

$C_D = 1.2 - .7\ P_D - .2\ P_I$	From Figure 4.2
$P_I = .28$	Assumed
$\Longrightarrow\ C_D = 1.14 - .7\ P_D$	
$C_S = 6.8\cdot 10^{-3}\ e^{11\ P_D}$	From Figure 4.9
$C_T = C_S + C_D$	By definition

FIGURE 5.2 Safeguards System Cost Curves

$C_{MCA} = 6.8\cdot 10^{-3}\ e^{11\ P_D}$	From Figure 4.9
$C_{PS} = 1.2\cdot 10^{-10}\ e^{25\ P_I}$	From Figure 4.10
$C_S = C_{MCA} + C_{PS}$	By definition
$P_I = .4 \ln (C_S - 6.8\cdot 10^{-3}\ e^{11\ P_D}) + .91$	Solving

4 Curves:	C_S	
a	.036	From Figure 5.4
b	.072	
c	.143	
d	.286	

FIGURE 5.3 Diversion Cost Curves

$C_D = 1.2 - .7\ P_D - .2\ P_I$	From Figure 4.2
$P_I = 6.0 - 3.5\ P_D - 5\ C_D$	Solving

4 Curves:	C_D	
a	.963	From Figure 5.4
b	.914	
c	.864	
d	.814	

Figure 5.7. Calculations in Support of Figures in Chapter 5
(page 1 of 3)

FIGURE 5.4 Optimal Setting of P_D and P_I for Four Cases

Formulate as a constrained optimization problem, with constraint on C_D:

$$\underset{P_I,\, P_D}{\text{Min}}\ C_S = \underset{P_I,\, P_D}{\text{Min}}\ \left| C_{MCA} + C_{PA} + \lambda(1.2 - .7\,P_D - .2\,P_I) \right|$$

$$\left.\begin{aligned} P_I^* &= .04 \cdot \ln \lambda + .72 \\ P_D^* &= .09\,\ln \lambda + .20 \end{aligned}\right\}\ \text{Solve by differentiation}$$

Compute C_D, C_S, C_{MC} and C_{PS} from P_I^* and P_D^*

4 Points	λ
a	.5
b	1.0
c	2.0
d	4.0

Assumed

FIGURE 5.5 Tradeoff Between C_D and C_S

$$P_I = .6312 + .44\,P_D \qquad \text{Solve two equations in } P_I^*,\ P_D^*,\ \lambda \text{ above}$$

$$C_D = 1.2 - .7\,P_D - .2\,P_I \qquad \text{Constraint Equation}$$

$$\left.\begin{aligned} P_I &= 1.23 - .558\,C_D \\ P_D &= 1.36 - 1.297\,C_D \end{aligned}\right\}\ \text{Solve above}$$

$$C_S = 6.8 \cdot 10^{-3}\, e^{11\,P_D} + 1.2\ 10^{-10}\, e^{25\,P_I} \qquad \text{From Figure 4.9}$$

$$C_S = 2.48 \cdot 10^{4}\, e^{-13.96\,C_D} \qquad \text{By substitution}$$

Figure 5.7 (page 2 of 3)

FIGURE 5.6 Sensitivity Analysis for P_D^*

$P_D^* = .09 \ln \lambda + .20$ From Figure 5.4

Probability of Attempt: P_A

Doubling P_A has the same effect as doubling λ

Value assigned to each death: V_D

Deaths account for roughly half of consequences (see Figure 3.7)

C_D proportional to $\frac{V_D + 1}{2}$

Correspondence:

λ	V_D	C_D
.5	0	.46
1	1	.92
2	3	1.8
3	5	2.7
4	7	3.6

Probability of Working Device

$C_D \approx .62 + 5.92\ P_W$ From Figures 4.2 and 3.5

Correspondence:

λ	P_W	C_D
.5	--	
1	.05	.92
2	.20	1.8
3	.35	2.7
4	.50	3.6

VI. SUMMARY AND CONCLUSIONS

In this report we have discussed briefly several aspects of the analytical methodology being developed in conjunction with LLL. The main topics were:

- Analytical approach: a tool for integrating cost and risk information used to make safeguards decisions
- Preliminary risk assessment models: for diversion attempts and their consequences
- Analysis using these models: sensitivity analysis and criteria evaluation to determine appropriate levels of plant safeguards.

This concluding section highlights several insights in these three areas.

Analytical Approach

The decision on "how safe" a safeguarded nuclear facility should be depends on a tradeoff between diversion risk and the cost of reducing that risk. Given the decision to build the plant, the optimum safeguards level is one at which the cost of further risk reduction exceeds the benefit of lower risk.

In order to make this tradeoff, the decision-maker must have quantitative information on the risks and costs. Because of the uncertainties and complexities associated with risks and costs, quantitative models of the factors that influence the risk/cost tradeoff have been developed. Taken together, these form the safeguards evaluation framework. In the beginning stages of this analysis, the models are highly aggregated with simple structures. These models are then successively refined as sensitivity analysis shows which elements have the most impact on safeguards decisions.

In addition to serving as a guide for additional analysis, the models provide effective tools for communication. They give a broad picture of the kinds of factors being considered, how these factors are interrelated, and how the quantitative information about these factors is used to make a decision. As the models are made more complex in order to reflect important aspects of the problem with greater precision, aggregated models are used to summarize the outputs of complex models. Thus, the aggregated models are used throughout the analysis: in the early stages, they provide the preliminary assessment that indicates how the evaluation will be made and which results should be sought; at the end of the project, they are used to summarize analytical results and show the implications of these results for the primary decisions.

Insights From Preliminary Models

The most striking conclusion from analysis to date is the low expected value of annual consequences from SNM diversion from a reprocessing plant. If this conclusion is supported by later work, many public policy decisions could be legitimately questioned. However, this conclusion could be invalid for two reasons:

- Preliminary probabilistic estimates in the Consequence Model are not realistic
- Expected value of consequences is not an adequate characterization of risk.

The first possibility can be dealt with through further explicit evaluation of the probability and consequences of nuclear incidents. The second point may require additional research on the appropriate risk attitude for public policy decisions involving low-probability events. However, based on the state of the art in decision theory, a strong argument can be made for using expected values when the assets of the exposed population are large relative to the magnitude of the consequences.

In the Diversion Model, most of the expected amount of SNM diverted per year is attributable to Sequence 1, a heavily-armed attack on the plant. For this sequence, MC&A plays no role in preventing the theft.

The second-highest contribution to the expected quantity of diverted material comes from Sequence 4, in which there is a very low probability of detection by MC&A or interruption by physical security.

The major cost related to an attempt comes from hypothesized shutdown for material inventory given a detected inside attempt. It is assumed the plant would be out of commission for two months, leading to a $10 million opportunity cost in foregone reprocessing.

The major factors in the Consequence Model are the consequences of an atomic detonation, evacuation, and extortion attempts.

Model Refinements

The analysis has highlighted several areas where refining these models could substantially improve the safeguards decisions. Better models of safeguards system costs and associated uncertainties are the most noticeable need. Without them, it is meaningless to try to set safeguards requirements. An aggregated model of the cost of the open-ended fuel cycle is also necessary to make the overall decision on whether or not to reprocess spent reactor fuel.

The Diversion Model should be enhanced first for Sequences 1 and 4. The areas worthy of refinement in the Consequence Model are the sensitive factors mentioned above. The linkage between the Diversion and Consequence Models should be refined beginning with the information concerning the sophistication of the adversary.

Research Areas

Risk attitude toward low-probability events is clearly crucial to safeguards decisions. This area has not been the focus of much decision-theory research to date.

A second research need is formal procedures for aggregating detailed probabilistic information (such as that produced by the LLL assessment procedure) in a form that can be used by both aggregated models and decision-makers. This report has demonstrated the value and use of such aggregated information; however, as yet the formal aggregation procedures have not been established.

A third area of research is the development of models of NRC and civil authorities' responses to extortion attempts or bomb threats. The decision analysis framework advanced in this report will provide a solid foundation for that work. The results of this analysis clearly depend on the reactions of authorities in these cases.

REFERENCES

1. C.A. Bennett, W.M. Murphy, T.S. Sherr, "Societal Risk Approach to Safeguards Design and Evaluation," U.S. Energy Research and Development Administration, ERDA-7, June, 1975.

2. I. Sacks, et. al., "Material Control System Design: Test Bed Nitrate Storage Areas," Lawrence Livermore Laboratory, May, 1978.

3. R.V. Brown and P. Feuerwerger, "A Macro Model of Nuclear Safeguards Effectiveness," Decisions and Designs, Inc., March, 1978.

4. I. Sacks, "Sequence Categories," Project Memorandum, Lawrence Livermore Labs, January 13, 1978.

5. WASH 1400, "An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants," USAEC, August, 1974.

6. General Electric Company "Compatibility Assessment of Safeguards Material Control Measures Against Covert Diversion of Nuclear Materials from a Commercial Fuel Reprocessing Plant, report number FBRD-00069, November, 1977.

7. S.M. Barrager, B.R. Judd, D.W. North, "The Economic and Social Costs of Coal and Nuclear Electric Generation," prepared by Stanford Research Institute for the National Science Foundation, USGPO Stock Number 038-000-00293-7, March, 1976.