A METHODOLOGY FOR THE ASSESSMENT OF THE PROLIFERATION RESISTANCE OF NUCLEAR POWER SYSTEMS

Topical Report*

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NOTICE

ABSTRACT

A methodology for the assessment of the differential resistance of various nuclear power systems to misuse for the production of nuclear weapons is developed. In the context of this study, a nuclear system comprises a particular fuel cycle and the political/institutional framework in which it operates. The latter may be country-specific.

The methodology is based on the principles of Multiattribute Decision Analysis, wherein a set of indices or attributes which characterize the proliferation resistance of nuclear systems is defined and evaluated for particular systems. Emphasis has been placed on delineating the logical structure of the problem, rather than on rank ordering the various systems of interest via techniques which aggregate the attribute values in a consistent manner. However, examples of the application of decision analysis in the latter situation have also been given to illustrate the potential of this approach to the proliferation problem.

TABLE OF CONTENTS

CONTENTS (continued)

CONTENTS (continued)

CONTENTS (continued)

CONTENTS (continued)

CONTENTS (continued)

FIGURES

FIGURES (Continued)

TABLES

TABLES (continued)

CHAPTER I

INTRODUCTION AND ORIENTATION

The purpose of the MIT methodology development effort(1) was to develop a logical framework that can be used by experts and decision makers to gain a better appreciation of how adoption of various nuclear power systems might differentially affect the proliferation of nuclear weapons.

The aim of the United States and other nations is to inhibit proliferation by deploying nuclear systems that will discourage non-nuclear-weapons states from attempting to go "nuclear" (or "almost nuclear") or from "backing into" a nuclear weapons capability. Two programs, a national- the Non-proliferation Alternative Systems Assessment Program (NASAP) - and an international- the International Fuel Cycle Evaluation (INFCE) program- have been initiated by the United States to evaluate alternative nuclear power systems in order to identify such proliferation resistant systems.

In making a balanced overall choice among possible nuclear systems, proliferation resistance is only one of many concerns; others are: (a) resource utilization; (b) economics, (c) safety, (d) environmental impacts; and (e) technological maturity. Hence, it is of interest to learn not only to compare one system with another with respect to proliferation resistance, but to point out ways in which the outputs of this study can be used as inputs into a broader study. This might involve difficult tradeoffs between proliferation resistance and some of the other above mentioned concerns.

Initially an attempt was made to assess indices of proliferation resistance for a prototypical potential proliferator. However, it soon became apparent that various countries were so different in: industrial infrastructure, scinetific know-how, economic capability, resource sufficiency, and geopolitical outlook that it was logical to concentrate on developing approaches that would shed light on whether one system was more proliferation-resistant than another for a given country with a given nuclear-weapons aspiration level--quality and number of weapons. Only after understanding this task would it be appropriate to attempt a paired comparison of two systems for a given country, integrated over all aspiration levels--keeping in mind the possibility that the degree of proliferation-resistance can affect and be affected by these aspirations.

Suppose a given nuclear system is being considered for widespread adoption. If this system were adopted, it would be important to know whether or not a given country by a given horizon date (e.g. 2010) would pass some nuclear-weapons threshold (or a series of thresholds) and, if so, what level of nuclear weapons capability it would attain. Given the inevitable uncertainties in projecting future developments, it would be relevant to consider the nature of the changes in assessments of these possible occurrences, first for this system and the given country, then for different systems for the given country, and finally for different countries... and then to repeat this whole exercise for different time horizons. We believe that this is what experts and decision makers must explicitly or implicitly think about as they try to balance proliferation-resistance concerns against other factors. Our study has a much more modest aim. We hope to provide a framework that can be used to organize and synthesize technical information about nuclear proliferation resistance as an input to others who have to make broader judgments concerning the wisdom of pursuing various nuclear scenarios.

Even though, comparatively speaking, we concentrate on the technical, scientific part of the proliferation-resistance problem, even here the goal of objective quantification is largely illusory. There are many relevant "evaluators" or "attributes" that characterize the proliferation resistance, e.g., monetary cost, time, difficulty, etc.

and not only must we identify a set of such attributes that captures what we mean by proliferation resistance, but we must develop a methodology for addressing inevitable tradeoff questions. Some of our readers will, we suspect, balk at going as far as we do in quantifying values and tradeoffs; this is a matter of taste and experience (and some faith). Nevertheless, we hope that they will think hard about our structuring of the qualitative though process that one should go through in thinking about this problem. This structuring, we feel, represents our main contribution to date. However, it may be appropriate at some point to address proliferation policy questions using some of the more sophisticated tools of decision theory,e.g., techniques dealing in a consistent way with tradeoffs and resolving differences of opinion among experts. It is in this spirit that an attempt has been made to provide a reasonably self-contained and complete discussion illustrating how decision theory can be applied in this case.

The numbers that we do introduce are meant only to be suggestive and pedagogically instructive; they are not meant at this stage to guide policy. Nevertheless, we take some comfort from the fact that the formal analysis using these numbers has resulted in conclusions that match the informal, independent judgment of several experts.

We assume throughout that our analysis of various nuclear systems (with respect to proliferation resistance) can be done independently of levels assumed by other non-proliferation characteristics of the systems. The validity of this assumption will be examined during the second phase of NASAP--during the so-called "integrated" assessment of the systems.

Our emphasis will be on technological and institutional factors directly related to the fuel cycles. We recognize that there are other (non-fuel-cycle dependent) means that can contribute to the prevention of the spread of nuclear weapons; e.g., those that influence incentives and disincentives. Indeed, the latter are probably at the heart of any viable non-proliferation strategy. Nevertheless, we will not consider them in our analysis, because we are interested in examining that part of proliferation resistance that depends on the fuel cycle per se.

This report is organized as follows: In Chapter II, we structure the assessment of proliferation resistance as a dual decision problem. The first is the choice that the international community must make regarding the deployment of several alternative nuclear systems, and the second is the choice that a would-be proliferator country must make among several possible ways to proliferate. Then, based on this problem structure, we present a summary of the methodological framework that can help decision makers assess the differential proliferation resistance of alternative systems.

In Chapter III, we define the proliferation resistance attributes, that is, we examine the choice problem of the would-be proliferator and we assess the attributes or evaluators that characterize the resistance of a particular way of proliferating.

In Chapter IV, assuming that the would-be proliferator would act rationally, we show how the attributes can be used to compare alternative systems with respect to their proliferation resistance. To facilitate the illustration of the methodology, we restrict our considerations to a "mini world" consisting of three alternative systems and two countries.

In Chapter V, we relax the assumption of "rational" behavior and extend the methodology to cover uncertainties about the behavior of the would-be proliferator.

CHAPTER II

METHODOLOGY SUMMARY

II.1 Problem Structure

The assessment of proliferation resistance can be structured as a tree with many branches. The branches describe partly the decision problem of the international community and partly that of the would-be proliferator. They are shown schematically in Figure II.1 and include the following.

II.1.1 Decision by International Community

The square node in Fig II.1 depicts a choice that must be made among alternative systems by a collectivity of nations including the United States. Of course, the decision can be made by the United States only, but the methodology need not be so restricted.

II.1.2 Alternative Systems

Each branch emanating from the square node represents an alternative system (s) defined as a "full" or "partial" nuclear fuel cycle together with all accompanying institutional constraints (including inspection and verification procedures) imposed upon its operation and control. For a given institutional pattern of constraints, some examples of alternative technical systems are: (a) Light Water Reactor (LWR), once-through cycle, with enrichment and spent-fuel storage permitted in all countries; (b) LWR, once-through cycle, spent-fuel storage but no in-country enrichment; (c) LWR, once-through cycle, no in-country enrichment and spent fuel shipped to an international depository; (d) LWR, plutonium recycle, enrichment and reprocessing permitted in the country, etc. We reiterate: the determination of each alternative system involves consideration of both technological characteristics and accompanying institutional constraints.

There is a mind-boggling set of possible alternative systems, as we are defining our terms, but we suspect that when the time comes for hard decisions to be made there will be only a handful of viable contenders. The vast bulk of possible systems will be ruled out by pragmatic, political concerns.

The widespread adoption of a particular system might result in proliferation of nuclear weapons. This proliferation can be "measured" in terms of specific countries each of which acquires particular weapons capabilities.

II.1.3 Countries

Each specific system (s) may be used by a potential proliferator country (c), a country that might try to acquire nuclear weapons through this system. The list of potential proliferators can be either an exhaustive enumeration of all such countries or gorups of country-types. Though in structuring the problem this way, we implicitly assume that every alternative system will be available for adoption in all non-nuclear weapon states, some unlikely combinations can be easily eliminated--such as the full LMFBR cycle in a small developing country.

Following the tree in Figure II.1, we imagine that some system(s) has been adopted in country (c). We next posit several possible nuclear-weapon aspiration levels for country (c).

II.1.4 Aspiration Level

The nuclear-weapons aspiration level is defined in terms of target values for the quantity and quality of weapons available at given times (plus rates of production). From a practical point of view, we envisage employing an aspiration scale with a half-dozen values from level 0 (nothing) to level 1 (a crude demonstration-type, nonderivable explosive device)... to level 5 (a sizeable stockpile of powerful bombs that could be delivered by missiles and that would be a threat even to major powers). The problem of interest is to assess the likelihoods that, given a system (s) a particular country(c) with a certian nuclear-weapons aspiration (a), will achieve various capabilities. Obviously there will be an interactive effect: aspirations will certainly affect achievements, but also a realization of the difficulties involved in achieving a given status will in turn affect aspirations. This is the nub of the problem. Although we shall not formally address these intertwining considerations (aspirations and achievements) we shall present technological information in such a way that experts and decision makers can more easily assess the relative contributions of each alternative system to the proliferation of nuclear weapons. Continuing our imaginary path down the tree, we consider the choices of country(c) with aspiration (a) given the availability of system (s).

II.1.5 Possible Choices by Potential Proliferator

Given that system (s) is chosen by the international community, country (c) (the potential proliferator), imbued with a hypothesized aspiration level (a) will have to decide [2] (represented by the diamond in Figure II.1) to proliferate via (s) along any one of several possible prolifeation pathways.

We difine a proliferation pathway as the mode of operation of the proliferator as well as the points of the fuel cycle from which weapons material will be diverted. For example, a possible proliferation pathway consists in covertly diverting spent fuel from the spent-fuel-storage facility, clandestinely constructing a reprocessing facility separating the plutonium from the spent fuel and fabricating the weapons.

The list of the proliferation pathways includes also independent pathways, i.e. pathways that lead to the acquisition of nuclear weapons through the use of nuclear facilities and materials that are independent of the adopted commercial nuclear power alternative system. These pathways are examined along with each alternative system since their relative attractiveness to the proliferator might depend on the particualr alternative system. For example, the reprocessing of the nuclear fuel irradiated in a small production reactor will be easier for a country with commerical reporcessing capability and experience than it would if such capability and experience does not exist.

Along any pathway the would-be proliferator will encounter various difficulties, inconveniences, and stumbling blocks, all of which we collectively call "proliferator resistance". Our next task is to indicate how one might evaluate this resistance.

II.1.6 Attributes of Proliferation Resistance

We will express the proliferation resistance in terms of a set of five attributes which we feel captures the essence of the issues that must be resolved by a would-be proliferator. These attributes are:

(a) Monetary Cost

(b) Weapon Development Time

(c) Inherent Difficulty

(d) Weapons Material

(e) Warning Period

We present the rationale for this set of attributes in Chapter III where we also elaborate on their meaning. Some of them, as for example the "Inherent Difficulty", are rather diffuse concepts that must be further subdivided into subattributes in order to give them operational meaning. Numerical or other measures of the attributes for a specific example are presented in Chapter IV.

Let us assume for a moment, that the only criterion that the potential proliferator-country (c) will use in choosing a particular pathway (p) is its proliferation resistance. Then, our first aim is to put ourselves in (c)'s shoes and figure out his best i.e., lest-resistant, pathway (p) for a given alternative system (s) and nuclear weapon aspiration (a).(3) To do so we "score" each pathway

(p) for given (s,c,a) on our five proliferation-resistance attributes as shown schematically on the bottom graphs in Figure II.1. Such a multidimensional scoring may suffice to eliminate pathways as non-contenders of choice by (c). A non-contender is a pathway that is more resistant on all the attributes than at least one other pathway. Of course, if there is a pathway that is less resistant than all the other pathways, on all the attributes the analytic task is greatly simplified. Unfortunately, such cases are rather rare and usually, even after the elimination of non-contenders, we are left with several pathways that can not be compared in the straightforward way just cited. Thus, for example, given (s,c,a) pathway (p') may be more resistanct than (p") on inherent difficulty and less resistant on a time or on a cost attribute. The choice among such pathways might entail making tradeoffs between attributes and there is no objective way of doing this. Judgment must intervene.

While there do exist protocols for asking experts tradeoff questions that can lead to a single numerical overall composite score for the porliferation resistance of a scenario (s,c,a,p) we note that experts might disagree about some of these numerical tradeoff judgments. Thus, one can expect disagreement about relative system rankings or perhaps agreement, but for different reasons. The methodology that is used in making these judgmental reductions is called "multi-attribute utility thoery" (MAUT) or the theory of "conjoint measurement" [6]. A summary of the part of MAUT that is used in this work is given in Appendix A.

II.2 Systematic Evaluation

Structuring the problem in the manner just cited, we can proceed with the ranking of fuel-cycle systems by starting from the bottom of the "tree" and climbing up to the top as follows.

II.2.1 Attribute Assessment

Each branch of the tree specifies a unique combination of a pathway (p) through which a country (c) is trying to achieve a particular nuclear weapons aspiration level (a) via nuclear system (s) which is deployed in the country. For these specific conditions the numerical or other measures of the proliferation-resistance attributes can be assessed. We will denote these measures by x_1, x_2, x_3, x_4, and x_5 for the five attributes monetary cost, weapons development time, inherent difficulty, weapons material, warning period, respectively. When this is done for all the pathways, a table of the form of Table II.1 will be generated. The asterics in this table will be replaced by the attribute measures.

Table II.1

Evaluation of Proliferation-Resistant Attributes for Various Pathways for Country (c) with Nuclear Weapons Aspiration (a) and for System (s)

	Proliferation Resistance Attributes				
Pathways	Monetary Cost	Weapons Development Time	Inherent Difficulty	Weapons Material	Warning Period
1	*	*	*	*	*
⋮	⋮	⋮	⋮	⋮	⋮
p	*	*	*	*	*
⋮	⋮	⋮	⋮	⋮	⋮

II.2.2 "Rational" Ranking of Pathways

Given a table of the form of Table II.1, simple inspection will determine the pathways that are "dominated" by others. A pathway is "dominated" by another if the measure of each attribute of the first is equal to or less preferred than the corresponding measure of the second. Once the dominated pathways are excluded, the remaining pathways form the so-called "efficient frontier." Comparison between any two pathways of the efficient frontier is no longer that straightforward, since some of the attributes will have more preferred values for one pathway while others will have more preferred values for the other pathway. To compare two pathways or points of the efficient frontier the preferences of the proliferator over the various values of the attributes should be established. The techniques of Multi-Attribute Utility Theory can now be used. If pathways differ greatly on these attributes, the techniques may be quite involved. However, in many cases pathways will have many attribute scores in common and then the techniques can be considerably simplified and made more transparent.

For a given (s,c,a) we seek the least-resistant pathway--call it (p*)-- and we can then give a proliferation-resistance score r(s,c,a,p*) to the combination (s,c,a,p*).

There is a methodological problem, however, that complicates the issue. For even if we assume that we know the preferences of the proliferator, it is not necessarily true that he will make a "rational" analysis before deciding whether and how to proliferate. In the absence of such an analysis, he might choose other "nonoptimum" pathways that are dictated by specific bureaucratic and scientific factors within his country. If such factors are taken into consideration, an alternative ranking of the various pathways might result. For that reason, a proliferation resistant score should consider how likely it is that various proliferation paths be followed; these likelihood assessments should reflect the specific conditions within country (c) as well as historical evidence. Details about such considerations are given in chapter V.

II.2.3. Resistance and Aspiration

Let us for a moment hold system (s) and country (c) fixed. As stated before, there are several nuclear weapons aspirations that (c) might have. We would expect that country (c) would adjust the level of its nuclear weapons aspirations according to its perceptions of the degrees of proliferation resistance that it confronts. For example, if aspirations a_i and a_j present country (c) with the same degree of resistance we would expect that (c) would strive for the "higher" aspiration. To enable us to infer what country (c) would do if (s) were adopted, the following table may be useful.

TABLE II.2

Evaluation of Proliferation-Resistant Attributes for the Most Likely Pathway that Country (c) will Follow for Various Aspirations and for a Given System (s)

Aspiration Levels	Most Likely Pathway	Proliferation Resistance Attributes x_1	x_2	x_3	x_4	x_5
⋮	⋮	⋮	⋮	⋮	⋮	⋮
a_1	p_1	*	*	*	*	*
⋮	⋮	⋮	⋮	⋮	⋮	⋮
a"	p"	*	*	*	*	*
⋮	⋮	⋮	⋮	⋮	⋮	⋮

[Note: x_1 to x_5 represent the headings in Table II.1]

This table presents the proliferation resistance of a system (s) to a country (c) for the various aspiration levels (a). The resistances are expressed in terms of the measures of the five attributes for the "most likely" pathway corresponding to each (a). Depending on the degree of sophistication of the analysis we can determine the "most likely" pathway in two ways: (1) as the "least resistant" pathway, determined on the basis of our perception of the rational behavior of country (c); and

(2) as a "composite" pathway that reflects the fact that all we know about the "rational" or possibly "irrational" behavior of the proliferator can be expressed in terms of the probability with which each possible pathway can be followed. Details for these two kinds of analysis are given in chapters IV and V, respectively.

By persuing Table II.2 analysts should be in a better position to reflect about the interactions between aspiration levels and proliferation-resistance levels. The "international community" should be interested not only in a potential proliferator's aspirations but in the conditional probabilities that he will actually achieve different levels of nuclear-weapons capabilities, given these aspiration levels. It is hoped that Table II.2 will be of assistance in making these judgments. For example, we could imagine that the following exercise might be completed on the basis on Table II.2.

Consider a simple scale that can be used both for nuclear-weapons aspirations and achievements. Let the levels be

$$a_0 < a_1 < \ldots < a_5$$

where a_0 denotes "no nucelar weapons involvement". Then, experts can, by considering the information contained in

Table II.2, assess the probability that country (c) will achieve a weapons-level a_j given that its aspiration was a_i. This probability is a quantitative assessment-in the opinion of the expert- of the likelihood that country (c) initially having aspirations a_i, will after examining the resistance of system (s) to other aspiration levels re-adjust its aspiration and end up with a weapons level a_j. These probabilities can be given in a table of the form of Table II.3.

TABLE II.3

Conditional Probabilities that Country (c) Will Achieve Various Weapons Levels Given Various Aspiration Levels and Unconditional Probabilities of These Aspiration Levels (for a Given System s)

Weapons Level	Probability of Aspiration	Conditional Probability of Achievement, Given Aspiration						
		a_0	a_1	a_2	a_3	a_4	a_5	(total)
a_0	*	*	*	*	*	*	*	1.00
a_1	*	*	*	*	*	*	*	1.00
a_2	*	*	*	*	*	*	*	1.00
a_3	*	*	*	*	*	*	*	1.00
a_4	*	*	*	*	*	*	*	1.00
a_5	*	*	*	*	*	*	*	1.00
	1.00							

On the basis of Table II.3 we can calculate the unconditional probability that country (c) will <u>achieve</u> each given weapons level. The probabilities can be given in a table of the form of Table II.4.

TABLE II.4

Unconditional Probabilities that Country (c) Will <u>Achieve</u> Various Weapons Levels (for a Given System s)

Weapons Level	Unconditional Probability
a_0	*
a_1	*
a_2	*
a_3	*
a_4	*
a_5	*
	1.00

All this may seem much too complicated. But there is no need to follow all these proposed steps. For example, one might wish to skip Table II.3 and assess Table II.4 directly, keeping Table II.2 in mind. Or even more simply one might wish to assess merely the probability for aspiration and for achievement of (a_0) and not to bother with finer breakdown of (a_1) to (a_5). But some way or another someone has to think these thoughts..., either formally or informally.

II.3 Comparison of Systems Across Aspirations and Countries

In our imaginary climbing up to the top of the tree in Figure II.1, we are now just past the "diamond" depicting the choice problem of the potential proliferator. At this point we can assess--as described in the previous two sections-- the probability that if system (s) is adopted, country (c) will achieve a particular weapons level (a). These probabilities provide a means for comparing systems for a given country and weapons-level. Thus, if the probability that country (c) will achieve weapons level (a) for system(s') is less than that for system (s"), we can conclude that (s') is more resistant than (s") for country (c) and weapons level (a). Of course, we could use the probability that given (s), country (c) will achieve (a_0)-- no weapons at all-- and thus, compare the various systems for a given country. In general, we could assign to each combination of country and aspiration level (c,a) an importance measure. Then, for a given system (s) we could weight the importance measures for all possible combinations (c,a) with the probabilities that a particular (c,a) will obtain. Thus, each system will be characterized by this average importance measure which can be also viewed as a measure of its proliferation resistance (or vulnerability).

As we proceed to work backwards through the tree, however, the synthesis becomes less technical and more political. An example of intercomparisons of systems across countries and aspirations is presented in Chapter IV.

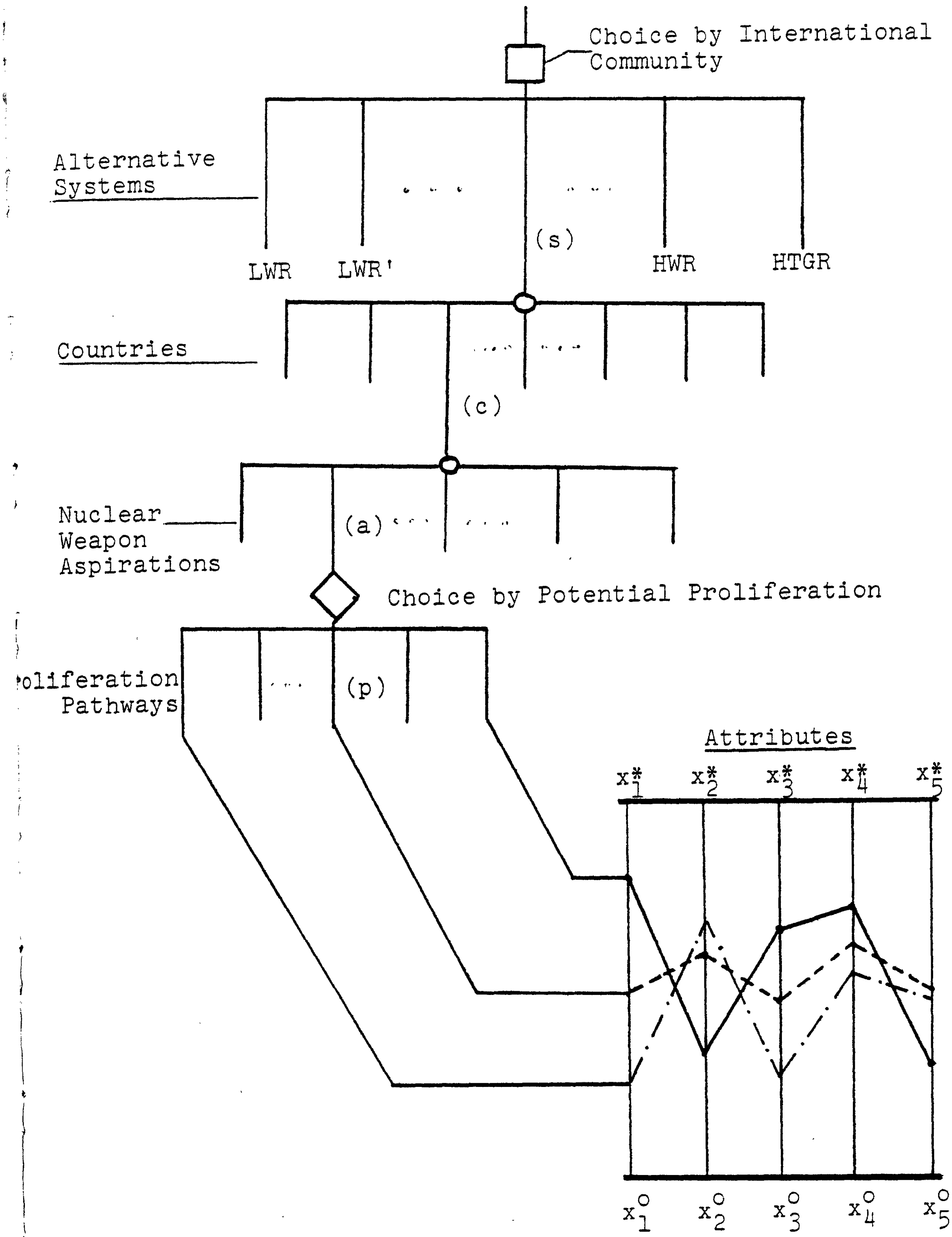

Figure II.1 Tree for Nuclear Proliferation Problem

CHAPTER III

DECISION BY POTENTIAL PROLIFERATOR

III.1 General Remarks

Given a nuclear system, suppose that a potential proliferator--a country (c)-- with a specific nuclear weapons aspiration sets as its objective the choosing of the least resistant pathway that leads to the achivement of the aspiration. Because no single measure of this objective exists, perhaps the would-be proliferator will disaggregate the overall objective into finer and finer subobjectives until each subobjective can be associated with a single measure or an "attribute". The value of each attribute will represent the degree to which the associated subobjective is accomplished, and the set of attributes might provide a means to evaluate the overall objective.

The disaggregation of the objective into subobjectives can be regarded as a hierarchy of levels of disiderata such that the achievements at a given level contribute to the achievements at a higher level, whereas at the lowest level of disaggregation each subobjective admits a measure-- an attribute-- the value of which characterizes the achievement of the subobjective.

An attribute can be either quantitative or qualitative. In either case, however, its value should permit the decision maker to judge the extent to which the associated subobjective has been achieved.

Unless discretion is exercised, the disaggregation of the objective into subobjectives may result in a cumbersome proliferation of attributes. For example, some attributes may be less important than others and, therefore should be disregarded. Moreover, some attributes may be important but insensitive to changes from alternative to alternative. As such they can be disregarded in intercomparisons of the merits and demerits of the alternatives.

This discussion suggest that the selection of the attributes should be regarded as evolutionary in nature. In other words, for a set of possible alternatives a preliminary set of attributes can be defined. Then, the consequences of each alternative are expressed in terms of the attributes, the relevance and importance of each attribute is assessed, and the process is repeated for a set of attributes.

In general, the set of attributes should be: (1) complete; i.e., cover all aspects of concern to the problem at hand; (2) operational; i.e., be meaningful to the decision maker so that he can understnad the implications of the alternatives and it should facilitate explanation to others; (3) <u>nonredundant;</u> i.e., avoid double counting of characteristics of the alternatives. Redundancies are introduced: (a) if there is a functional relationship among attributes measured in the same units. For example, if cost C_A of A and cost C_B of B are two attributes, then they are redundant with the total cost $C = C_A + C_B$. Indeed, if only the total cost C is important, then C_A and C_B should not be used. If the individual costs C_A and C_B are important then C should not be used; (b) if the importance of an attribute lies in its impact on another attribute. For example, if one attribute is an imput and the other is a dependent output then, they are redundant; (4) <u>minimum size</u>, i.e., the number of attributes should be kept as small as possible. As the number of the lowest-level subobjectives increases it becomes easier to identify attributes to measure the degree of achievement of each subobjective. However, the preference assessment becomes less and less tractable. A compromise should therefore be made between the ease of characterization of each alternative and the difficulties created by the intercomparison of alternatives.

III.2 Structuring the Objectives of the Potential Proliferator

The major objective of the proliferator is to establish the pathway with the least resistance that will allow him to achieve a nuclear weapons capability. This objective is pursued under certain constraints that are dictated by existence of a specific nuclear system. The system is defined by the type of fuel cycle that is available, the type of facilities that are permitted within the national boundaries of the would-be proliferator, the various international agreements about the use of such facilities and, in case of illegal actions, the sacntions that will be imposed. Under these constraints the would-be proliferator tries to choose the pathway that best complies with national needs, capabilities and constraints while at the same time trying to maximize the likelihood of successful completion of the task. Hence, the major objective can be divided into the following two subobjectives (see Figure III.1).

B1. Increase the "attractiveness" of the pathway

B2. Increase the likelihood of success.

Subobjective B1 contains all the factors that make a particular pathway more desirable than another, conditional on the successful completion of the effort. Subobjective B2 contains all the factors that affect the probability

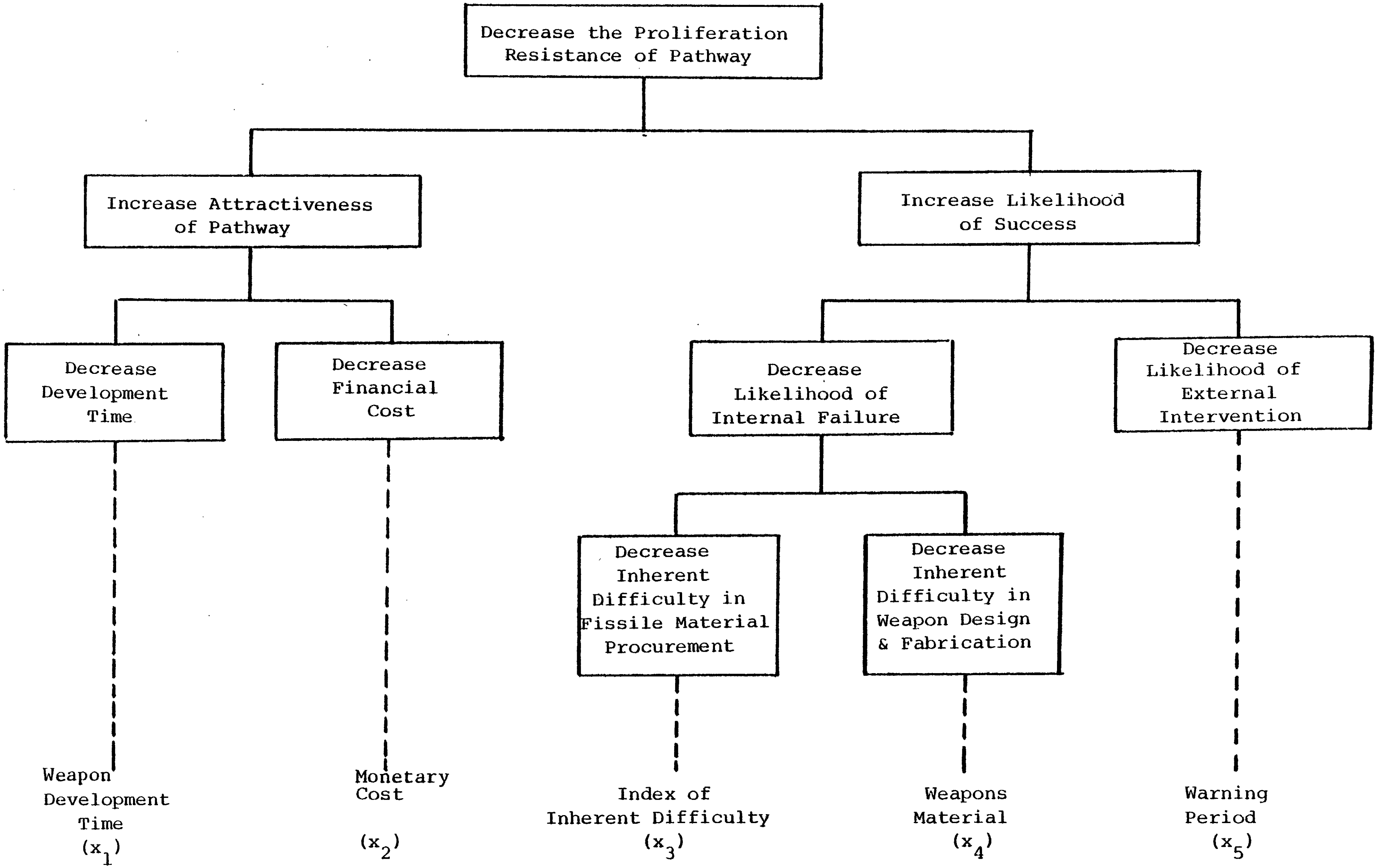

Figure III.1 Decomposition of major objective into subobjectives that the proliferation effort will be successful. This second subobjective has of course an impact on the attractiveness of a pathway but we can avoid redundancy if we agree to include any attractiveness value of the second subobjective in the relative weighting of the subobjectives and exclude from the first any factors that affect the likelihood of success.

B.1 "Attractiveness" of pathway

Here we include all the factors that affect the decision of the proliferator to choose a particular proliferation pathway, conditional on the fact that the acquisition of weapons through this pathway is certain. Two factors that characterize attractiveness are the amount of time necessary for the development of the weapons and the associated financial cost. A pathway is the more attractive, the less time and the less money it requires for its accomplishment. We can, therefore, subdivide B1 into two other subobjectives.

B1.C1. Decrease the weapons development time.

B1.C2. Decrease the monetary cost.

Another factor that characterizes the attractiveness of a pathway is the military utility of the resulting nuclear weapons. However, we have included the utility of the weapons in the definition of the aspiration and therefore, we need not reconsider it here.

B.2. "Likelihood" of success

Here we include all the factors that increase the probability of successful completion of the effort. This probability depends on problems peculiar to the proliferator himself and on the likelihood of intervention by the international community. We can, therefore, subdivide B2 into two other subobjectives.

B2.C3. Minimize the likelihood of failure due to internal causes.

B2.C4. Minimize the likelihood of external intervention.

Let us now examine each of these two subobjectives in some detail.

B2.C3. Minimize the likelihood of failure due to internal causes.

Factors that affect the likelihood of failure are related to the difficulty inherent in carrying out the proliferation tasks. We can separate the proliferation effort into two tasks: (a) acquisition and preparation of fissile material; and (b) weapons design and fabrication.

Hence, we can subdivide the objective of decreasing the likelihood if internal failure into two other subobjectives:

B2.C3.D1. Decrease the inherent difficulty in the acquisition and preparation of fissile material.

B2.C3.D2. Decrease the inherent difficulty in the weapons fabrication

A single measure for the difficulty inherent in the acquisition and preparation of the fissile material does not exist. Nevertheless, an index can be generated by further decomposing this subobjective in the manner discussed in Appendix B. For many intercomparisons, however, this index may not be necessary. Then, a simpler qualitative characterization of this difficulty, such as low (Low), medium (Me), and high (Hi) may be sufficient.

Similarly, a single measure for the difficulty inherent in the weapons design and fabrication does not exist. This measure is, however, so much dependent on the chemical nature and composition of the fissile material that the material (called weapons material) itself can be used as an attribute of this difficulty. Since the difficulty inherent in the procurement of fissile material and in the design of the nuclear explosive effectively covers the factors that affect the likelihood of failure due to internal causes, and since corresponding measures of effectiveness exist, no further subdivision is necessary.

B2.C4 Minimize likelihood of external intervention

Factors that affect the likelihood of failure due to external intervention are related to the likelihood of detecting the proliferation effort, the likelihood of sanctions by the international community, and the nature of these sanctions. Since the sanctions are part of our definition of an alternative system, they need not be considered independently for each pathway. The same is true for potential regional reactions. By choosing one pathway instead of another the proliferator can only affect the likelihood of being detected and the likelihood of application of sanctions. The likelihood of applica-tlion of sanctions depends on the particular country that tries to proliferate, the rules set forth by the interna-tional community, and the period of time available for application of sanctions namely, the period of time between detection and completion of the weapons aspiration.(4) By definition of the pathways, the country and the rules of the international community are all identical for the de-cision problem in question. Hence the proliferator can only influence the period of time available for application of sanctions. Moreover, this time period--the warning period--provides a measure of detectability of a particular pathway because the longer the warning period the higher the detectability. Since the warning period effectively expresses and measures the likelihood of external intervention, this objective need not be further subdivided. For reasons explained in Section III.3.5 and in Appendix C we do not measure the warning period in terms of time, but rather in terms of the fraction of the task that remains to be completed at the moment of detection. A more detailed analysis of this attribute is given in Appendix C.

The developed hierarchy of objectives is shown schematically in Figure III.1. The five subobjectives of the lowest level and the corresponding attributes are further examined in the following section.

III.3 The Proliferation Resistance Attributes

III.3.1. Weapon Development Time

Weapon Development Time is the time required to produce the first weapon starting from the first "proliferation action." If more than one weapon desired, the time to complete the whole arsenal can be easily calculated by adding to the development time the time necessary for the production of the additional weapons. This latter time is the same for all pathways since the rate of weapon production is part of the weapons aspiration and hence the same for all pathways.

The first "proliferation action" is the first action towards the acquisition of nuclear weapons. The first action might be the serious commitment by a government or a first preparatory step by a group within the governmental or the scientific bureaucracy.

In general, the development of nuclear weapons can be dicided into four phases:

1) Preparation. Planning, education and training of necessary personnel, research and development, non-nuclear material procurement, design and construction of the necessary facilities, non-weapon testing, etc.

2) Nuclear material acquisition. Diversion of material (fissile) from fuel cycle.

3) Nuclear material processing. Converting of the acquired material from the form suitable for fuel cycle operation to weapons usable form.

4) Nuclear weapon fabrication. Assembly of nuclear material into weapons.

If we denote the time necessary to complete each of the above steps by t_i (i=1,2,3,4) then, the weapon development time will be a function of the t_i's. Both the values of these times and the function that defines the weapon development time depend heavily on the proliferation path. For example, for given values of the t_i's, the weapon development time T, can be anywhere between the minimum value T_{min} and a maximum value T_{max} where T_{min} equals the t_i that has the largest value, and T_{max} equals the sum of the t_i's. The minimum value might correspond to an all-overt, "quick-grab" scenario, while the maximum to an all-covert, step-by-step scenario. Of course, the individual values of the t_i's depend on the particular pathway, i.e. on the mode and rate of the proliferation approach.

The "first proliferation action" is the beginning of the proliferation phase, i.e., it is any action or step taken that is not necessary for the functioning of the alternative system as a power system regardless of whether such action is "illegal" or not. Thus, for the purposes of our analysis, if an alternative system provides only for reactors operating in a country with fresh fuel supplied from outside and spent fuel shipped away, then, the beginning of any study concerning enrichment or reprocessing is considered to be the"first proliferation action". This is so, because neither of these two processes is necessary for the operation of the power system. In general, for a given alternative system, a given country and a given weapon aspiration, several proliferation pathways are possible. [3,5] These pathways could lead to the acquisition of nuclear weapons at a different cost, different time, different degrees of difficulty and different probabilities of success. Nevertheless, once a particular proliferation pathway is defined, the exact sequence of the various actions is defined and, therefore, the degree of overlapping of the four time periods is known. This overlapping is shown schematically in Figure III.2.

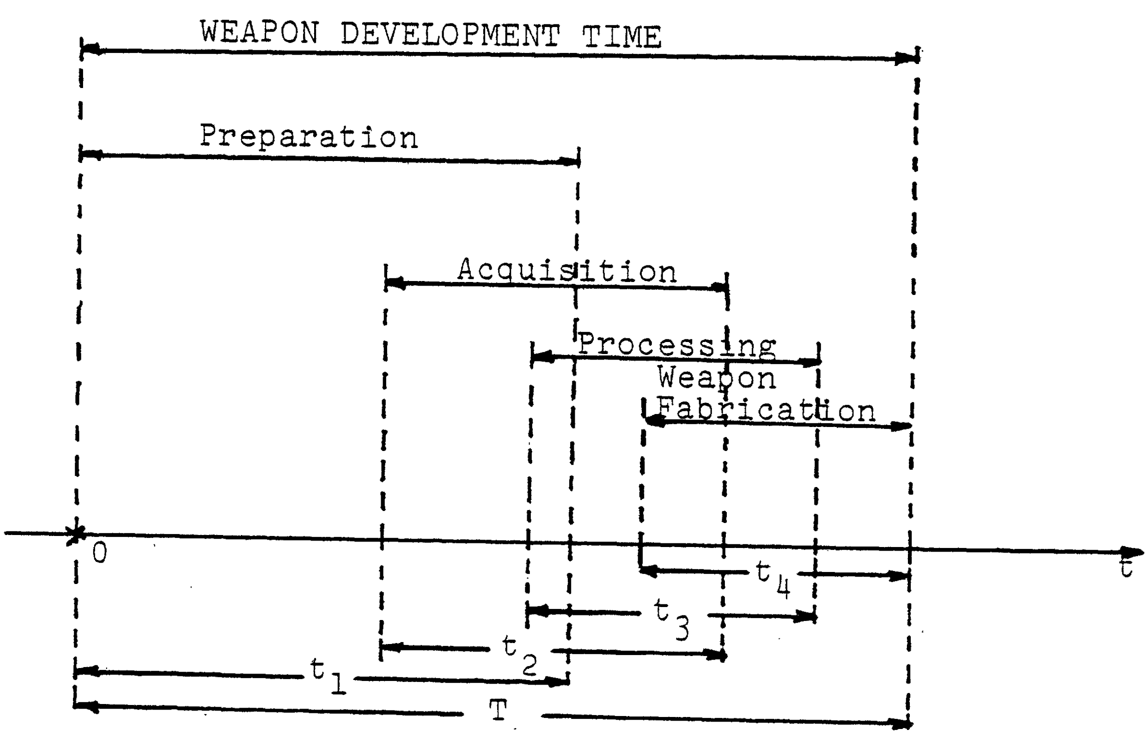

Figure III.2: Weapon Development Time for a <u>given</u> proliferation scenario.

For all the proliferation pathways, however, the corresponding weapon development time starts with the first action towards proliferation and ends with the completion of the first weapon (or the desired arsenal).

The general significance of the weapon development time might be (apart from its influence on the other attributes) assessed according to whether it is sufficiently long to preclude (or hinder) the potential proliferator from meeting his desired weapon development schedules and thereby reduce the attractiveness of a particular pathway.

III.3.2 Monetary Cost

The total financial cost of achieving the aspired nuclear weapon capability. This cost consists of the following three components.

1) All direct capital and operating costs. These costs include all direct cost for equipment and material (non-fissile) purchases, personnel payments, construction or facilities as well as effects on the economy from the deversion of resources to that effort.

2) Cost incurred due to nuclear energy misuse. If the fuel management scheme is altered to improve the "quality" of the fissile material, the nuclear power reactors will not operate at their optimal mode for the generation of

electricity and thus, a financial cost will be incurred. This component of the cost includes the cost of the unused available energy in the fuel as well as the cost for replacing this energy by other means.

3) Nuclear fuel-cycle related costs resulting from sanctions

If as a result of the construction of nuclear weapons (demonstrated or otherwise confirmed) the institutional constraints on the fuel cycle result in the interruption of the production of electricity from nuclear energy via, e.g., cutoff of the supply of fresh fuel, a financial cost is incurred. This cost includes the cost of a slowdown or actual shutdown of the operation of equipment of huge capital investment (nuclear reactors) and it also includes cost incurred from the transition to other forms of energy production.

III.3.3. Inherent Difficulty in Fissile Material Procurement

This attribute provides a measure of the difficulty inherent in converting fissile material into a form suitable for weapons. This difficulty increases the chance of failure of the proliferation effort and therefore has some deterrence value. The attribute includes those characteristics of the alternative system that increases the difficulty of proliferating and that cannot be properly reflected by the cost and time attributes. Such characteristics are: the scientific and technological complexity of the process, the scientific personnel requirements, and the organizational and management sophistication. In evaluating this attribute, we will assume that the scientific personnel and technological expertise necessary for the complete operation of an alternative system are fully developed and available to any country that is using the system for the generation of electricity. Accordingly, the characteristics mentioned refer to the additional effort required to manufacture nuclear weapons, starting from the given system.

The conversion of the nuclear fuel into weapons usable from requires one or both of the following processes: (a) chemical separation of fissile material; (b) isotopic separation of fissile material. If the difficulty of each of these two processes is scored as low (Lo),medium (Me), or high (Hi), then the difficulty associated with a particular pathway will be characterized by (X,-), (-,Y) or (X,Y) depending on whether only the first, only the second, or both processes are needed, where X and Y stand for Lo, Me, or Hi. We feel that such a scoring for the inherent difficulty will be adequate for most pathway comparisons. Nevertheless, a cardinal scale for the inherent difficulty has been developed for use in cases exhibiting subtle differences. The development of this scale and a demonstration of its use are presented in Appendix B.

III.3.4. Weapons Material

The type of the weapons material (fissile isotope and concentration) provides a proxy attribute for the degree of difficulty associated with the design and fabrication of the weapon. The desired weapons quality is predetermined for each pathway (through the weapons aspiration) and, therefore, the weapons material involved in a pathway can be used as a measure of the problems that must be overcome to achieve the desired weapons quality.

Four types of fissile material are considered: (a) Reactor-Grade Plutonium (RG-Pu); (b) Weapons-Grade Plutonium (WG-Pu); (c) Highly Enriched Uranium-233 (HE-U233); and (d) HIghly Enriched Uranium 235 (HE-U235).

These four types of weapons material can be ranked in order of decreasing (or increasing) difficulty in the weapons design and fabrication and thus provide an ordinal scale for this difficulty.

III.3.5 Warning Period

We define the warning period as the fraction of work that remains to be done for the completion of the weapons objective after the proliferation effort has been detected.

An ongoing proliferation effort can be detected at any instant during the development time. The detection can be achieved through various means, e.g., national intelligence or confirmed violation of IAEA safeguard arrangements. For a given pathway (proliferation scenario) the amount of work completed at any instant of the development time is known. Thus, we know at the moment of detection the fraction of th task completed and hence the fraction (y) of the task that <u>remains</u> to be done. The fraction y of the work that remains to be done is used as an attribute instead of the time remaining to the completion of the first weapon, because it is highly unlikely that the proliferator will continue to operate according to the initial scenario after the detection. If, for instance a proliferation pathway requires a development time of 3 years for a covert effort and, a detection takes place 2 years after the start, it is very unlikely that the proliferator will continue at the same pace as before and thus, that a warning period of 1 year exists. Most likely he will continue with a crash effort (if at all) and thus, what is of importance is what remains to be done. This point is further explored in Appendix C.

The detection of a proliferation effort can take place at any point in time. The time elapsed from the beginning of the proliferation up to the detection is, therefore, a random variable and the same is true for the fraction of the completed work and the fraction that has yet to be completed. The warning period is thus a random variable taking values from 0% (no detection) up to 100% (detection at the very start) with an associated probability distribution function. The probability distribution of the warning period depends on and, therefore, reflects all the factors that affect the likelihood of detecting an ongoing proliferation effort.

In summary, this attribute provides a measure of the relative ease with which a proliferation effort can be detected and a measure of the period available for taking actions, e.g., applying sanctions against the proliferator before his objective is achieved.

III.4 Adequacy of the Proliferation Resistance Attributes

As stated in Section III.1 the set of attributes should be complete, operational, nonredundant and minimum in size.

We think that the set of five attributes just cited is complete, i.e., covers all the areas of concern to a potential proliferator. The development of this set was evolutionary in nature. We began by examining a rather extensive list of attributes proposed by various parties and found that all the entries in that list measure in some way the degree of achievement of one of the five subobjectives presented in Section III.2. The list of attributes that we examined is presented in Appendix D along with brief comments explaining why we think that each of these attributes is included in the five that we proposed, or is not important.

In addition, we think that the set of attributes is operational, since decision makers and experts can understand the implications of an alternative by examining its "scores" on the five attributes. There is a potential problem, however. Because both technical and politico-strategic aspects must be considered, it is conceivable that a technical attribute such as inherent difficulty or weapons-material quality may not be as meaningful to political scientists as it is to technocrats. Hence, although each attribute may be individually meaningful to decision makers with relevant expertise, when taken as a set the attributes may not be meaningful to a decision maker of a particular background (scientists-engineers versus lawyer-political scientists). As we will see later in the paradigm of this methodology (Chapter IV), a large part of the analysis is immune to this problem. This is because the proliferation pathways can be separated into groups such that those belonging to a group present the same degree of difficulty in the fissile material procurement and in the weapons design and fabrication. The pathways belonging to such a group will,therefore, be compared only with regard to the nontechnical attributes and hence the analysis could be made even though the decision maker(s) are lacking a thorough and complete understanding of technical problems. This simplification notwithstanding, a point will be eventually reached in which tradeoffs will be necessary between "technical" attributes and "nontechnical" attributes. At that point, a possible solution might be the "fusion" of the two technical attributes--inherent difficulty and weapons material into one, namely the "probability of successful completion of the task" or equivalently "the probability of internal failure." Such a merging can be done by technical experts and the resulting measure will be meaningful to decision makers of nontechnical background. We conclude, therefore, that, in the sense of the discussion of this paragraph, the proposed set of attributes is operational.

The proposed set of attributes is also nonredundant. No consequences are counted twice since there is no attribute whose importance lies only on its effect on another attribute.

Some of the attributes could be further subdivided into subattributes. Yet, such a subdivision would increase the number of attributes to an extent that it will be difficult for decision makers to get a comprehensive idea of the resistance of a particualr pathway. We feel that five is sufficient for the assessment of the resistance of most pathways. There will be cases, however, for which a subdivision of one or more attributes will be necessary to account for subtle differences in the resistance (see in particular Appendix B). Nevertheless, the total number of attributes that need be considered will not necessarily be larger since in such cases the values of other attributes may be essentially constant, and hence irrelevant to a comparison among different pathways.

CHAPTER IV

APPLICATION - RATIONAL ANALYSIS

IV.1 General Remarks

As a demonstration of the methodology we will apply it to a "mini-world", consisting of 3 alternative systems, 2 countries, and two weapon aspirations. If we draw the decision tree of Figure II.1 up to the second node for this "mini-world" we would end up with 12 branches i.e., the 12 combinations of system-country-aspiration. For each of these combinations, the possible proliferation pathways will be defined and the "scores" of the five attributes for each pathway will be assessed. Thus we will generate 12 Tables--one for each system-country-aspiration combination--each containing the pathways and the values of the attributes for each pathway. (see Table II.1).

Next we will demonstrate how decision makers and experts representing the preferences and values of the would-be proliferator country, could choose among the pathways of a table the one that is-in their opinion- the least resistant. This pathway will represent (in terms of the scores of the five attributes) the resistance of the corresponding system (s), to the proliferation effort of country (c) having a specific weapons aspiration (a).

The assessment of the least resistant pathway will be done by using qualitative arguments and the ideas of dominance and extended dominance among alternatives. A numerical composite "score" will not be derived. Only in Appendix E will we show how the Multi-Attribute Utility Theory can be used to derive a single numerical score for the resistance of a given proliferation pathway.

The selected pathways with the least proliferation resistance can be put together in a table that will show the resistance of each system to a proliferation effort by a particular country with a given nuclear weapon aspiration. These resistances will be expressed in terms of the five attributes. We will show then, how decision makers representing the preferences of the international community or the United States can use such a table to make judgments about the relative proliferation resistance of various systems.

Throughout this chapter we will assume that a careful "rational" analysis will be performed by the proliferator in assessing the pathway through which he will try to fulfill his nuclear weapons aspiration. This assumption does not hold in general, and will be relaxed in the next chapter. Nevertheless, the ideas and procedures presented in this chapter will be used in the more complete analysis, and for the sake of clarity we present them under the simplifying assumption of "rational" behavior.

The merit of an analysis considering the would be proliferator as "rational" decision maker having all available information at his disposal, lies not in the likelihood of the realization of such a situation but rather in emphasizing that the resistance of an alternative system to the proliferation of nuclear weapons is different for different countries since it depends on the characteristics, preferences and priorities of each particular country.

Finally, we note that the numbers we use in our examples as well as the conclusions we draw, are for demonstration purposes only and are not meant to guide policy.

This chapter is organized as follows. Section IV.2 presents the definitions of the alternative systems, countries, weapons aspirations and proliferation pathways considered in our example. Section IV.3 to IV.4 show how the first four proliferation resistance attributes are calculated for a given pathway. Section IV.5 discusses the attribute "warning period" and introduces the concepts of utility and certainty equivalent. Section IV.6 demonstrates how decision makers and experts of a particular country would assess the least resistant pathway for a given alternative system and nuclear weapon aspiration.

Section IV.7 shows how decision makers representing the international community or U.S. point of view, can rank the alternative systems based on their resistances to the proliferation effort of various countries having various weapons aspirations. The analysis in this section is qualitative. Section IV.8 introduces a quantitative approach to the problem addressed in Section IV.7. Finally, Section IV.9 constitutes an epilogue to this chapter.

IV.2 Alternative Systems- Countries- Aspirations and Pathways

The definition of an alternative system includes the technical characteristics, the institutional constraints and the sanctions that may be applied in case of violations. The technical characteristics and institutional constraints of the 3 systems we are using in our example are given below. For the purposes of this analysis, we will assume that the sanctions are similar to what might happen today in case of a proliferation: some political pressure, cancellation or curtailment of credits, technical exchanges, agreements of cooperation, including those involving nuclear assistance. We will call this kind of sanctions light sanctions. The three systems that we consider are as following:

System I: Light water reactors--uranium-once-through cycle.

Only reactors are allowed within the boundaries of a non-weapon state with fresh fuel supplied from outside and spent fuel stored in the country; light sanctions.

System II: Light water reactors--denatured thorium cycle. Only reactors are allowed within the boundaries of a non-weapon state with fresh fuel supplied from outside and spent fuel stored in the country; light sanctions.

System III: Light water reactors-- uranium with Pu recycle cycle. The fuel is preirradiated Mixed Oxide (MOX). Only reactors are allowed within the boundaries of a non-weapon state. Fresh fuel is shipped in, spent fuel is stored in the country; light sanctions.

We consider two countries B and C.

Country B. Country B is developing but has substantial natural resources and the potential to become a fully industrialized nation within the next 20 years.

Country C. Country C is smaller than B both in size and in development potentail. Presently, it is in a less developed stage than B and has no significant industrial infrastructure.

Each of the two countries have one of the following two nuclear weapons aspirations.

Aspiration a_1. A crude, nondeliverable explosive.

Aspiration a_2. Ten weapons of military quality (deliverable by airfighthers) to be completed within one year from the construction of the first weapon.

Next, we define the pathways that can lead to the fulfillment of the aspirations for each and every of the 12 combinations of system, country and aspiration. The definition of a proliferation pathway includes the mode of operation, the point of diversion of nuclear fuel and the weapons material. We distinguish two phases of the proliferation procedure: (a) the preparation phase, or the prediversion phase during which research and development, design and even construction of faciliteis can take place but during which, no nuclear material has been diverted from the commerical operation; and (b) the diversion phase during which nuclear fuel is being or (has been) diverted. Furthermore, we consider two modes of operation of each of those phases: covert and overt. Overt operation implies that activities are conducted at a higher rate and with fewer precautionary measures than covert. In other words, the probability of detecting an overt operation is higher than that for a covert operation, but not necessarily equal to one. These two modes of operation combined with the two phases of the proliferation yield four combinations of porliferation modes.

(1) Covert Preparation- Covert Diversion

(2) Covert Preparation- Overt Diversion

(3) Overt Preparation- Overt Diversion

(4) Overt Preparation- Covert Diversion

Of these four only the first three are considered, because the fourth represents a rather unlikely[5] mode of operation.

For the systems considered in this example, nuclear fuel can be diverted in either of two ways: (a) the front end, namely from the fresh fuel supply; and (b) the back end, namely from the spent fuel. Furthermore, there are two types of material with which nuclear weapons can be constructed: uranium and plutonium. When the various ways of diversion and types of fissile material are combined with modes of operation, the proliferation pathways are generated. The pathways considered for each of the twelve combinations of system-country aspiration are given in Tables IV.1 to IV.12 respectively. For example, pathway 1 in Table IV.1 (C-C-SF) corresponds to covert preparation (design and fabrication of necessary facilities), covert diversion of spent fuel, reprocessing, Pu extraction and weapon fabrication. In the same table pathway 2 corresponds to covert preparation but overt diversion (seizure of) spent fuel, reprocessing, Pu-extraction and weapon fabrication.

Along with the pathways that depend on the alternative system, we consider also an independent pathway. This pathway consists in constructing a production reactor [(6)], irradiating uranium not related to the fuel cycle, and recovering the plutonium from the irradiated fuel.

The list of pathways presented for each system-country-aspiration combination is not meant to be complete, but is adopted for illustration purposes only. Other pathways could be added with different modes of operation.

Our next task is then to assess the values of the five attributes for each proliferation pathway.

IV.3 Development Time and Cost

The development time is defined for a given pathway as the time from the "first proliferation" action up to the construction of the first weapon. For each pathway a time schedule of the type shown in Figure IV.1 can be generated.

	TASK	Time - Schedule (years)					Cost ($M)
		1	2	3	4	5	
1	R&D, Facilities-Weapon Design						10
2	Construction of Facilities						15
3	Material Acquisition						
4	Material Processing						2
5	Weapon Fabrication						3
							30

Figure IV.1. Time schedule for proliferations pathway no. 1 of Table IV.1

From such time-schedules the development time for the various pathways can be derived. From the same table the total cost directly associated with the construction of weapons can be calculated if the cost of each subtask is assessed. This cost includes all direct capital expenditures as well as operating costs, salaries, capital service etc., integrated over the relevant periods of time and discounted to the present. For pathways that involve diversion of fresh fuel, the cost of replacing the lost energy is also included (only in equivalent fuel not in capital for new equipment). Because of the ambiguity in the definition of sanctions, costs resulting from their application are not included. We hasten to add, however, that in a complete analysis the nature of the sanctions should be well defined and financial costs resulting from them included, since they might play an important role in the differentiation of the various pathways and in particular between the alternative-system dependent and the independent pathway.

From tables of the form shown in Figure IV.1, we can estimate the development time and cost associated with pathways of the twelve combinations of system-country-aspiration. Here we assume that a single estimate is possible. We will see later how we can include uncertainty in the analysis, i.e., a range of estimates and associated probabilities.

IV.4 Inherent Difficulty and Weapons Material

For a given pathway the necessary procedures for the separation of the fissile material from the nuclear fuel are predetermined. Specifically, pathway 1 to 3 in Table IV.1 require chemical separation of Pu from the spent fuel, and pathways 4 to 6 isotopic enrichment of uranium of the fresh fuel in uranium 235. Again, pathways 4 to 9 of Table IV.2 require chemical separation of uranium from thorium and then isotopic enrichment in uranium 233. The independent pathway requires the chemical separation of plutonium from the irradiated fuel.

The inherent difficulty in the procurement of the fissile material is scored by High, Medium, or Low in each of the two kinds of processes that are generally required i.e., the chemical separation and the isotopic enrichment. In scoring the inherent difficulty we considered the status of the relevant information, the level of radioactivity involved, and the existence of criticality problems (see also Appendix B). In addition, we considered the industrial and scientific capabilities of the country in question. For example, we scored the inherent difficulty of pathway 7 in Table IV.1 "Low" and that of 1 "Medium" because the former involves lower levels of radioactivity and a simpler clad-fuel separation procedure [8].

IV.5 Warning Period

The warning period or the fraction of the task that remains to be completed at the moment of detection of the proliferation effort is a random variable. Our first task with regard to this attribute is, therefore, the assessment of the uncertainties about it. In other words, we want to assess the probability with which the warning period, y attains each of the possible levels. This can be done by assessing the cumulative probability distribution function $F(y)$, namely the probability that the warning period will be less than or equal to a particular value y. The details of this assessment are given in Appendix C. By following one of the procedures described there curves of the form shown in Figure IV.2 can be generated for each pathway. In general, the probability distribution function depends on all the factors that affect the detectability of a pathway. In particular, it includes the possibility that for some pathways there will be no warning period ($F(0)$ is different from zero).

The question now arises: "How do we compare two pathways with uncertain warning periods?" The answer to this question is discussed in the following subsection.

IV.5.1 Certainty Equivalent for Warning Period

The comparison of two pathways with respect to the warning period is easy when we encounter situations as the one illustrated in Figure LV.3, namely when the probability that the warning is less than y for pathway 1

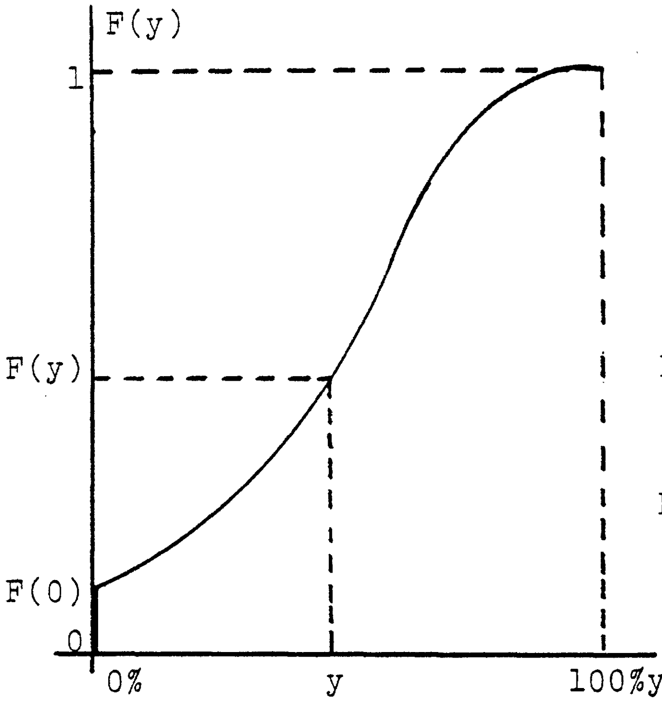

Figure IV.2 Cumulative distribution function for warning period (probability of y or less).

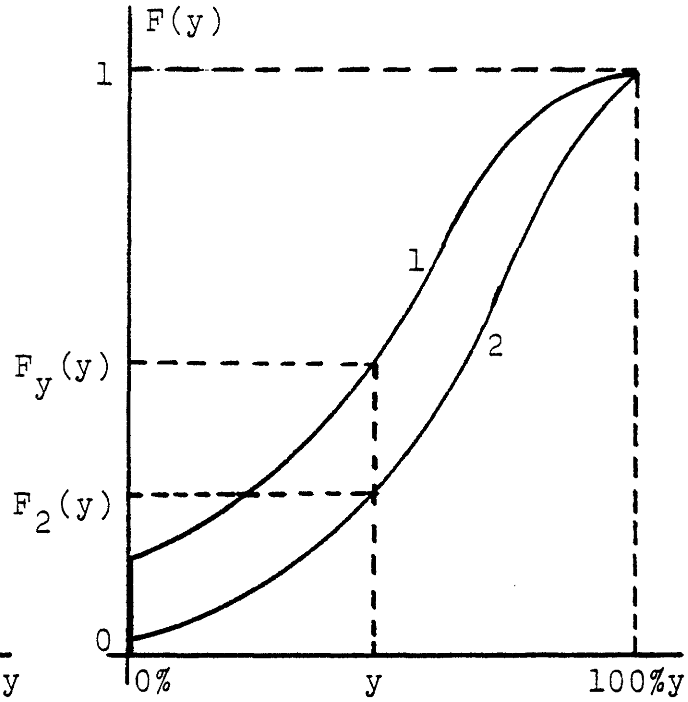

Figure IV.3 Probabilistic dominance $F_1(y) > F_2(y)$ for all y's.

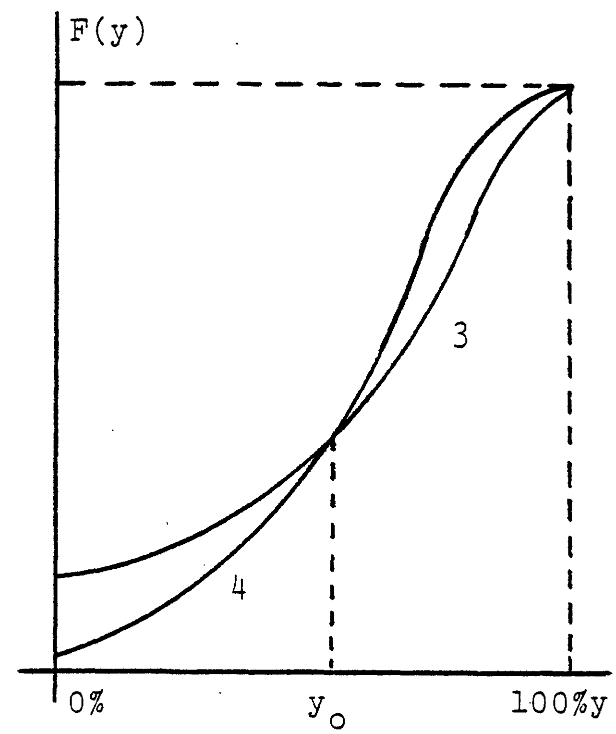

Figure IV.4 Intersecting cumulative probabilities functions.

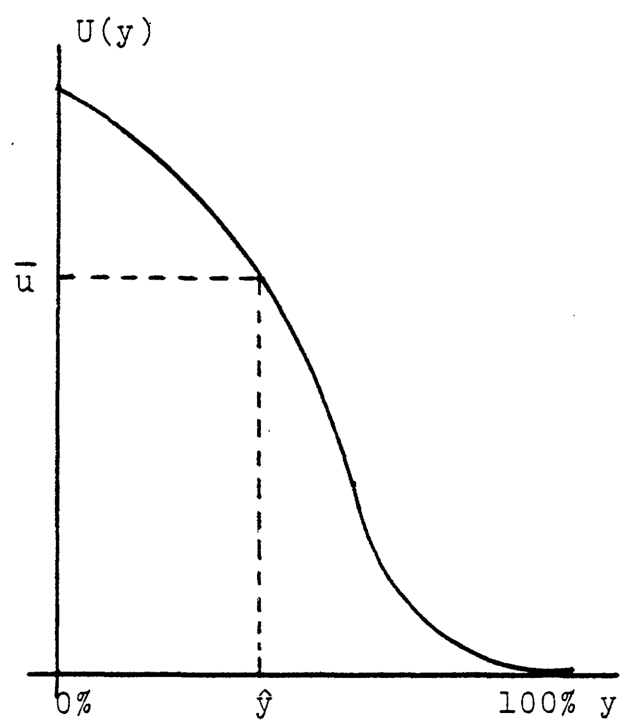

Figure IV.5 Utility function for woming period. Certainty equivalent ($\hat{y}$).

is always higher than that of pathway 2. Suppose that the proliferator always prefers a smaller value of the warning period to a larger one. Then, since for any value y the probability that the warning period will be less than y is higher for pathway 1 than for pathway 2, it follows that <u>as far as</u> the warning period is concerned, 1 is preferred to 2. Such <u>probabilistic dominance</u> is however, the exception rather than the rule. A more common situation is the one depicted in Figure IV.4 where the ordering of the probability values is different in different ranges of y. The choice among the two pathways is no longer that straightforward. In such cases the concept of certainty equivalent discussed below can be of help.

Suppose that a study indicates that the uncertain warning time has an associated probability distribution F(y), the probability of a warning time of y or less. We now can imagine the following question being posed to the would-be proliferator: Would you rather take your chances letting the warning time be governed by F, or would you just-as-soon settle for a warning time that with certainty occurs at $\hat{y}$. Naturally, the smaller the $\hat{y}$ is, the more desirable the certainty alternative. As $\hat{y}$ increases, the less desirable the certainty alternative becomes. We make a bold assumption: There is some value of y, called the certainty equivalent for which the uncertain option and the certainty option are indifferent in the opinion of the proliferator. Now there are, to be sure, systematic ways that a proliferator could use to analyze what his certainty equivalent should be, but that's a technical detail in our development. The point is we imagine that associated to the probabilistic characteristic, F(y), there is a certainty equivalent $\hat{y}$. We can think of $\hat{y}$ also as a single numerical value that summarizes the relevance of the entire distribution F, and in this case $\hat{y}$ is nicely interpretable.

In Appendix C we discuss the formal theory of utility analysis which can be employed to systematically examine the preferences and risk attitudes of the would-be proliferator and by formal means compute the certainty equivalent based on more basic, fundamental behavioral inputs. In the same Appendix we also present a numerical example of utility assessment and we describe how the certainty equivalents for the warning period shown in Tables IV.1 to IV.12 were calculated.

IV.6 Choice of Least Resistant Pathway-Dominance and Extended Dominance

In sections IV.2 to IV.5 we saw how we can generate the various pathways that can lead a particular country that has adopted an alternative system to the acquisition of nuclear weapons. Furthermore, we saw how we can assess the "scores" of the five proliferation-resistance attributes for each pathway. In this assessment we assumed that uncertainty exists only about the warning period, and we saw how such uncertainty can be "removed" by introducing an "equivalent" deterministic value. We can follow similar procedures if uncertainties exist about other attributes.(7) Thus, we know how to prepare tables like Table IV.1 to IV.12. Our next task is to infer how the potential proliferator's decision makers and experts would go about choosing the least resistant pathway. The first step in the choice procedure will be to divide the set of pathways into groups such that the members of each group have the same score in one or more attributes. If this is possible, then in choosing among the pathways of a group we need only consider a reduced number of attributes, i.e. those that don't have equal "scores", in this manner, we achieve a reduction in the dimensionality of the problem. In other words, we decompose the problem into several- as many as the groups- problems of smaller dimensionality. Usually such a decomposition will be guided by the nature of the pathways. For example, the pathways of Table IV.4

can be divided into three groups. The first consists of pathways 1 to 3 that involve diversion of spent fuel and extraction of reactor grade plutonium as weapons material under different operating conditions. The second consists of pathways 4 to 6 that represent different modes of diverting fresh fuel and enriching it into U235, and the third is the independent path.

Next, within each group, we will first exclude pathways that are dominated. Pathway i' dominates i" if all the attribute scores for i' are at least as preferred as the scores of i" and there is at least one attribute that has a score in i' that is strictly preferred to the corresponding score in i". Thus, we see that pathway 2 (in Table IV.1) dominates pathway 1 since both have equally preferred values for the development time, inherent difficulty and weapons material but 2 has more preferred values for warning period and cost.

After the exclusion of the dominated pathways we are left with pathways none of which are dominated by another. Thus, in the first group we have pathways 2 and 3. Pathway 2 is "better" than 3 in the values of the warning period and cost but 3 is better in the value of development time. Here judgment must intervene. We would ask ourselves [8] for example: "If it were possible to generate a new pathway 2' by starting from 2 and changing only the development time and the warning period i.e., if 2 is denoted [9] by

Pathway 2 = (2.0, 3%, M/-, RG-Pu, 15) (IV.7)

and 2' by

Pathway 2' = (1.5, ? , M/-, RG-Pu, 15)

could we adjust the warning period in 2' so that we are indifferent between 2 and 2'? In other words starting from pathway 2 how much more of warning period would we be willing to accept for a reduction of a half year in the development time? Let us suppose for a moment that the answer is "We would be willing to increase the warning period by 1% (from 3%-4%) to achieve a reduction of a half year." Such an answer means that pathway 2 could be replaced in Table IV.1 by pathway 2' or (1.5, 4%, M/-, RG-Pu, 15). But now we see that pathway 3 is dominated by 2' since the latter has the same scores as the former on all attributes but on the warning period and on the cost for which 2 has more preferred values. This means that 2' is preferred to 3 and since 2 and 2' are equivalent, we conclude that 2 is preferred to 3. In choosing between pathways 2 and 3 we used the idea of <u>extended dominance</u>

which formally can be stated as follows:

Let us suppose that we can partition the proliferation resistance attributes into two sets Y and Z such that the i-th pathway is described by $(\underline{y}_i, \underline{z}_i)$. Let us furthermore assume that for each pathway it is possible to "price-out" the y's in terms of the z's by tranforming each $\underline{y}$ to some base $\underline{y}^*$. For example for three pathways 1,2, and 3 we define equivalent pathways 1',2' and 3', respectively, such that

$$
\begin{aligned}
\text{Pathway } 1 &= (\underline{y}_1, \underline{z}_1) \sim \text{Pathway } 1' = (\underline{y}^*, \underline{z}_1') \\
\text{Pathway } 2 &= (\underline{y}_2, \underline{z}_2) \sim \text{Pathway } 2' = (\underline{y}^*, \underline{z}_2') \qquad \text{(IV.8)} \\
\text{Pathway } 3 &= (\underline{y}_3, \underline{z}_3) \sim \text{Pathway } 3' = (\underline{y}^*, \underline{z}_3')
\end{aligned}
$$

where "$\sim$" means "indifferent to". Then in comparing pathways i',2' and 3' we need consider only the z attributes since the y-attributes are all fixed at the common level $\underline{y}^*$. Thus, we can investigate the pathways for dominance relations in the reduced set of attributes z. Of course, this idea of extended dominace does incorporate some sub-objective judgment namely the reduction of $(\underline{y}_i, \underline{z}_i)$ to $(\underline{y}^*, \underline{z}'_i)$. In the example of pathways 2 and 3 of Table IV.1 that we considered in the previous paragraph, the set $\underline{y}$ consisted only of the development time, and furthermore it was possible to reduce this attribute to the common basis (1.5 years) by changing only one attribute of the $\underline{z}$ set (i.e. warning period).

In using the idea of extended dominance it is not always necessary to establish equivalent pathways by solving the indifference equations (IV.8). More straightforward approaches could be used. For instance, by a similar approach as for group one, we can determine that pathwya 5 is preferred to all pathways of group two (i.e. 4, 5,6 see Table IV.1) Then, we have to compare pathwasy 2 and 5 i.e.

$$\text{Pathway } 2 = (2.0,\ 3\%,\ \text{M}/-,\ \text{RG-Pu},\ 15) \qquad (\text{IV.9})$$

and

$$\text{Pathway } 5 = (5.0,\ 19\%,\ -/\text{H},\ \text{HE-U235},\ 250) \qquad (\text{IV.10})$$

Here we see that pathway 2 is more preferred than 5 with regard to all the attributes but the weapons material. Again we could try to use the idea of extended dominance by asking ourselves to define the value of the inherent difficulty for which we would be indifferent [10] between 2 and

$$\text{Pathway } 2'' = (2.0,\ 3\%,\ ?\ ,\ \text{HE-U235},\ 15) \qquad (\text{IV.11})$$

Of course any other attribute or combination of attributes could be used for compensating the decrease in difficulty in the weapons design and construction associated with the change from RG-Pu to HE-U235. Yet, such a procedure (solving IV.11) could be unnecessarily tedious. It may be possible to choose directly between pathways 2 and 2* where 2 is given by (IV.9) and 2* is given by

$$\text{Pathway } 2^* = (2.0,\ 3\%,\ -/H,\ \text{HE-U-235},\ 15) \qquad (\text{IV.12})$$

i.e. we might be able to answer directly the question: "Would we prefer to increase the inherent difficulty in the fissile material procurement from (M/-) to (-/H) in order to decrease the difficulty in weapon design and fabrication from the one associated with the use of reactor grade plutonium to the one associated with highly enriched U235?" If the answer is no, that is, if 2 is preferred to 2* then, since 2* is preferred to 5 (by dominance considerations) we can conclude that 2 is preferred to 5. If the answer is yes, then we proceed from 2* and construct $2^\dagger$ where

$$\text{Pathway } 2^\dagger = (2.0,\ 19\%,\ -/H,\ \text{HE-U235},\ 15)$$

and compare $2^{\dagger}$ to 2. If we prefer 2 over $2^{\dagger}$ then we also prefer 2 over 5 since $2^{\dagger}$ dominates 5. If we prefer $2^{\dagger}$ over 2 then we construct

$$\text{Pathway } 2^{\S} = (5.0,\ 19\%,\ -/H,\ \text{HE-U235},\ 15)$$

and compare $2^{\S}$ to 2. If we prefer 2 over $2^{\S}$ then we also prefer 2 over 5 since $2^{\S}$ dominates 5. It is noteworthy that in the above procedure we focused our attention at one attribute at a time and thus, the comparison of the pathways was easier than it would have been if we wanted to compare all the attributes simultaneously. Going back to the initial comparison of pathway 2 (Eq. IV.9) to pathway 2* (Eq. IV.12) let's assume that we would prefer 2 over 2* and thus that 2 is preferred to 5. We conclude, therefore, that from the first six pathways of Table IV.1, pathway 2 is the least resistant. The comparison of this pathway with 7 is deferred for a later subsection.

In this section we saw how the problem of choosing among various pathways can be simplified by using one or more of the following procedures:

(a) The reduction of the dimensionality of the problem by taking advantage of common bases (i.e. groups of pathways having the same value in several attributes).

(b) The process of dominance, i.e. excluding pathways for which there is another pathway having better or equal values on all the attributes.

(c) The process of extended dominance, i.e. using subjective judgment to reduce the values of a subset of attributes to a common base for all pathways and then exploring the idea of dominance for the remaining attributes.

In most instances one or more of these processes will suffice for the determination of the least resistant pathway. There are cases, however, for which such a procedure becomes tedious and, in addition, there is the danger of including in the analysis preferences and tradeoffs of the decision maker that are inconsistent. In such cases a more generally-structured quantitative analysis, such as the one presented in Appendix E, might be appropriate.

IV.6.1 "Business as usual" versus "Crisis" environment

In the previous subsection, in choosing pathway 2 (Table IV.1) over 3 (and 5 over 6) the implicit assumption was made that the value of decreasing the development time from 2.0 years to 1.5 years (and from 5.0 to 3.5 years) was not too great, at least measured in warning period units. Such a preference behavior on the part of the would-be proliferator might be characteristic of a "normal" environment in which a would-be proliferator will try to proliferate at a leisurely pace. If, however, there is the potential for a sudden crisis, e.g. a confrontation with a regional adversary, then the attitude towards the development time might drastically change. Furthermore, the whole set of preferences and value tradeoffs about warning period, probability of success, cost, etc. might also change. It is obvious, therefore, that the proliferation resistance of an alternative system depends not only on the country and the nuclear weapons aspiration but on the environment under which the proliferation takes place. In the remainder of this section we demonstrate how a choice between pathways 2 and 3 (Table IV.1) could be made assuming a "crisis" environment.

First, we will try to establish "how much" in terms of development time an increase of 3% (starting from 3% and going to 6%) in the warning period would be worth. Let us suppose that the answer is 3 months. We have thus established that pathway 2 = (2.0, 3%, M/-, RG-Pu, 15) is equivalent to 2' = (1.75, 6%, M/-, RG-Pu, 15). The next question would then concern the cost, i.e. "how much" development time would be equivalent to spending \$10 million -- starting from 2' with a cost of \$15 million and going to 2" with a cost of \$25 million. Let us suppose that the answer is 2 months. Then, we have established that 2' is equivalent to 2" = (1.6, 6%, M/-, R.G-Pu, 25). We can now compare pathways 2 and 3 since 2 is equivalent to 2" and 2" is dominated by 3. We conclude that 3 is preferred to 2" and therefore that 3 is preferred to 2.

Similarly we conclude that 6 is preferred to 5 and them, that 3 is preferred to 6. We see, therefore, that the consideration of a "crisis" environment changed the resistance of alternative system I from the one represented by pathway 2 to that of pathway 3.

We conclude this subsection by noting that comparisons such as the one described above (subsequent reductions of many attributes to a common basis) if repeated many times might include inconsistent assessments. For example, after examining many alternative systems each containing many pathways we might get a different tradeoff for the increase of the warning period from 3% to 6% with no underlying reason. Thus, in such instances a quantitative analysis such as the one described in Appendix E might be necessary if only for checking consistency.

IV.6.2 Adequacy of Reactor-Grade Plutonium as Weapons Material

In section IV.6 the comparison of pathway 2 to pathway 3 was made under the assumption that the difference in the difficulty associated with the design and construction of weapons from reactor-grade plutonium and the corresponding difficulty associated with highly enriched uranium was less (in value) than the difference in the difficulty associated with the chemical separation of the Pu from the spent fuel and the difficulty associated with the enrichment of uranium. Although such an assumption seems reasonable for a crude device there is not enough unclassified information to support the validity of a similar assumption for weapons of higher "quality", like those associated with aspiration a_2.[11] Since the relative proliferation resistance of the alternative systems depend heavily on this assumption, we considered two levels of difficulty associated with the design of weapons with R.G-Pu: small and large.

These two levels of the difficulty when combined with the two possible environments of "business as usual" and "crisis" create four sets of conditions. For this reason we performed the analysis four times. Thus, for each set of conditions the least resistant pathway of each of the twelve combinations of alternative system-country-aspiration was assessed using the procedures described in this section; the results are presented in Tables IV.13 to IV.16, respectively. In each table the resistance of an alternative system in a country having a given aspiration is presented in terms of the "scores" that the five proliferation resistance attributes have for the least resistant pathway.

Some comments about the "independent system" that appears in Tables IV.13 to IV.16 are appropriate at this point. In general the resistance of the "independent system" will depend on the alternative system that is adopted by the country in question. For instance, the difficulty in reprocessing the spent fuel from a production reactor in a dedicated facility is less if commercial reprocessing is allowed in the country than if it is not. Similar comments can be made about the probability of detection, cost, time, etc. Thus, in general, the independent system can be considered as an additional pathway for a given system-country-aspiration combination; this is the way in which the so-called "independent path" was incorporated into Tables IV.1 to IV.12. If the independent pathway associated with a given alternative system is the least resistant, then this pathway will represent the resistance of the alternative system. We might have cases in which the resistances of two alternative systems will be both represented by the independent pathway and yet, a comparison will be possible because the resistance of this pathway under one system is higher than under the other. Of course, we can always represent the resistance of a system by two pathways: (a) the least resistant among the pathways directly related to the system; and (b) the independent pathway.(12) In our example, it so happened that the resistance of the independent pathway for a given country and aspiration was the same for the three alternative systems. This was due to the identical institutional constraints for all three systems i.e., to the fact that the only difference in the systems was the type of the nuclear fuel. Thus, instead of considering three identical independent pathways -- one for each system -- we treated their common resistance as the resistance of a fourth "independent" system.

The information contained in Tables IV.13 to IV.16 can be now used in overall assessments of the relative proliferation resistance of alternative systems.

IV.7 Proliferation Resistance of Alternative Systems -- The International Community Point of View

In Section IV.6 we saw how the resistance of an alternative system to proliferation by a country having a specific nuclear weapons aspiration can be characterized by the resistance of the least resistant pathway. The assessment of the least resistant pathway for each system-country-aspiration combination is made from the point of view of the would-be proliferator. The results of such an analysis can be now used in an overall ranking of the alternative systems. In particular, we will see in this section how decision makers and experts expressing the point of view of some non-proliferation community; e.g., the London Suppliers Group can, by perusing tables similar to those derived in the previous section (Tables IV.13 to IV.16), make judgments about the relative proliferation resistance of an alternative nuclear system. Of course, we note once more that the numbers and the results of this example are for demonstration and discussion purposes only and are not meant to be conclusive.[13]

The first step will be to rank the alternative systems in order of decreasing resistance, for given proliferator-country and aspiration. This problem is one of making a decision with multiple objectives.[14] For instance, given Country B and aspiration a_1 (see Table IV.13) the problem is to rank four alternatives each of which is characterized by its "scores" on five attributes.

There is a methodological point, however, that should be mentioned here. The warning period is scored in terms of its certainty equivalent. In evaluating this quantity we used the utility function of the would be proliferator. Since we now look at the problem from a different point of view (non-proliferation community) we should use a different utility function. Assuming that the uncertainties in the value of the warning period are perceived similarly, systems I and II in Table IV.13 will be characterized by the same value of the certainty equivalent, albeit different from 3%. For this reason and for convenience, we did not recalculate the certainty equivalents. In a complete analysis, however, in which tradeoffs might be made between warning period and other attributes the certainty equivalents should be evaluated using a utility function that expresses the point of view of the non-proliferation community.

Once the new values of the certainty equivalents are calculated the procedures of dominance and extended dominance can be used if applicable. For this particular example we note (see Table IV.13) that alternative system III has scores on the five attributes that are less, or at most, equally preferred to the corresponding scores of systems II and I. Thus, system III is less resistant than systems II and I. Similarly, we note that system II is slightly more resistant than system I. Hence, we have established the following ranking in terms of decreasing resistance.

$$II > I > III$$

Comparing now systems III and IV we notice that IV is more resistant in development-time and cost attributes, less resistant in the weapons material attribute and equally resistant in the inherent difficulty attribute.(15) Assuming that the decrease in difficulty in the design and construction of a crude explosive associated with using weapons-grade instead of reactor-grade plutonium is worth an increase of a half year in the development time, we can conclude by dominance considerations that system IV is more resistant than III. Similarly we can conclude that IV is slightly less resistant than I, and thus we end up with the ranking presented in Table IV.17.

It is noteworthy that in this example comparisons between any two systems were made solely on the basis of the "scores" of the five attributes. In general, however, the possible sanctions (that are part of the system definition) should be also considered explicitly. Although some of the effects of the sanctions might be reflected in the "scores" of the proliferation resistance attributes, there might be other effects that are not included. As discussed in Chapter III, the reason for not considering attributes to describe such effects is that for a given system-country-aspiration combination they are the same for all pathways and, therefore, they do not contribute to the differentiation of the pathway. These effects are nevertheless important and should be always kept in mind both because they might affect tradeoffs among the attributes and because they might play a crucial role in comparing different systems.[16]

Once the ordering of the systems for a given country and a given aspiration is completed, the next step is to "combine" the rankings across the various aspirations into an overall ranking, keeping the country constant. If the same ordering of the systems has resulted for all the aspirations, then the "integration" over the aspirations is easy. We can use this common ordering as the ranking of the systems for that particular country. This is the case demonstrated in Table IV.17. There will be cases, however, for which the ordering of the systems will change as we move across the aspirations of a given country. Such an example is given in Table IV.18. Here again judgement must be used. Of course, whenever possible we will use dominance and extended dominance. If for example systems I and II were ranked 2-1 for aspiration a_1, and 4-3 for aspiration a_2, we would conclude that system I is less resistant than II regardless of the aspiration. Sometimes in order to explore the dominance idea we will have to go back to Tables IV.13 to IV.16. In Table IV.18, for example we note that for Country B and aspiration a_1 system II is ranked first, while system I is ranked second. This order is reversed for aspiration a_2 where system I is ranked second ahead of system II which is ranked third. Going back to Table IV.14 we note that for aspiration a_1 the difference in the proliferation resistance of systems I and II consists of the $5 million difference in the costs. For aspiration a_2, however, we note the differences in the first four attributes notwithstanding,(17) that system I requires $280 million more than system II to achieve the weapons objective. Thus, we conclude that the difference in the resistance of systems I and II for aspiration a_2 is much higher than that of aspiration a_1.(18) This conclusion, coupled with the assumption that the achievement of aspiration a_2 is more difficult than the achievement of a_1 leads us to the conclusion that the ordering of systems I and II for aspiration a_2 will characterize the overall ranking of these two systems for Country B.

Of course this line of thought could be further illuminated by considering the relative likelihood that Country B will have an aspiration a_2 instead of a_1.

Once we have achieved the ordering across aspirations for each country, our next task is to generate an overall ranking of the systems across the countries. Again, if it happens to have the same ordering for all the countries -- as it is the case in our example -- we naturally use this common ordering. If different orderings correspond to different countries then we will have to use judgement once more, and weight the importance of one country versus the other. We might have to go back to the ordering of systems for given country and aspiration and consider the combined importance of a country with a particular type of weapon capability versus another combination or, go even further back and examine Tables IV.13-to-IV.16. But in the end we can come up with an overall ordering.

The final rankings of the systems considered are presented, for the four sets of assumptions mentioned in subsections IV.6.1 and IV.6.2, in Tables IV.17 to IV.20. As it can be seen in these tables, the relative ranking of the systems depends heavily on the degree of difficulty associated with the design and construction of a_2 weapons with reactor-grade plutonium. For example, under a "business as usual" environment, system II (de-natured-Thorium cycle) can be either the most resistant (Table IV.17) or the least resistant (Table IV.18) among the first three systems, depending on how difficult it is to design and construct a_2-weapons with reactor-grade Plutonium. Similar results are obtained for a "crisis" environment (see Tables IV.19 and IV.20). As far as the effect of the "environment" is concerned, we note that the relative ranking of the three systems does not change with the environment. For a "business-as-usual" environment and with adequacy of RG-Pu, the ordering of the first three systems in terms of decreasing resistance is: II < I < III (see Table IV.19). An important difference in these two cases is however, the relative position of the independent system. For a "business-as-usual" environment the independent system is less resistant than systems I and II, while for a "crisis" environment the independent path becomes the most resistant. This is due to the rather long development time required by the independent path. On the other hand, if the difficulty associated with designing sophisticated weapons with reactor grade plutonium is relatively high, then the relative resistance of the independent paths does not change dramatically with the environment (see Tables IV.18 and IV.20). The ambiguity resulting from the difficulty associated with reactor-grade plutonium can be resolved with the availability of relevant information. The ambiguity resulting from the "business-as-usual" versus the "crisis" environment can be resolved if we treat the problem probabilistically as discussed in Chapter V.

The analysis presented in this section resulted in an ordinal ranking of the alternative systems with respect to their proliferation resistance. Although useful conclusions can be derived from such a ranking, the information contained in such ranking is not sufficient for an overall evaluation of the systems if other characteristics, e.g., economics and safety must be considered. For such comparisons we need a quantitative notion of the proliferation resistance i.e. a measure of "how much" more resistant one system is than another. In the next section we propose such a quantitative measure for the proliferation resistance.

IV.8 Nuclear Weapons Aspiration and Probability of Achievement

In the previous section we saw how decision makers and experts can, by using the information contained in Tables IV.13 to IV.16, make judgements about the relative ordering of alternative nuclear systems with regard to their proliferation resistance. Three stages of ordering were considered. First, the systems were ordered for a given country having a particular nuclear weapons aspiration. Next, the ordering was generalized across aspirations for a given country, and finally, an overall ordering across countries was determined. All three orderings were ordinal rankings, and although they contain useful information they do not provide a measure of "how much" more resistant a system is than another. In this section we will present a procedure that can lead to a cardinal ordering of the alternative systems. In particular we will present a way of achieving a cardinal ordering of the systems for a given country and aspiration.

The quantity we will use to measure the resistance of a system for a given country and aspiration is the probability that this country will fulfill this aspiration; i.e., its <u>probability of achievement</u>. Thus, if $p_i''(s,c)$ denotes this probability for system (s), country (c), and aspiration (a_i), we will say that system s' is more resistant than s" for country (c) having an aspiration (a_i), when $p_i''(s',c) < p_i''(s'',c)$. More generally, given a country we would like to know how the probabilities of achievement of the various aspirations are affected by the adoption of a particular alternative system.

The probability of achievement depends both on the likelihood that a given country wants weapons specified by the particular aspiration; e.g., the question of incentives and disincentives and on the resistance that an alternative nuclear system presents to this aspiration. We can formalize these dependencies as follows. Let $p_i'(c)$ denote the prior probability that country (c) has aspiration a_i. In our example $i=0,1,2$ where a_0, the "null" aspiration, represents the situation in which a country does not have nuclear-weapons aspirations at all. These probabilities reflect factors such as regional rivalties, prestige, etc... that affect the desire of a country to obtain nuclear weapons regardless of the way it will try to obtain them. Next, let $p_{ij}(s,c)$ denote the conditional probability that country (c) having aspiration a_i and having adopted system (s) will finally achieve a weapons capability specified by aspiration a_j. This dependence on aspiration level is important because the weapons capability achieved by a country which proliferated through a given system is not necessarily the same with the one it had initially in mind. This might happen either because the country tried to achieve its initial objective and failed, or because it adjusted its aspiration after considering the relative proliferation resistances. If, for instance, a country that initially had aspiration a_1 examines the resistances of the adopted system to aspirations a_1 and a_2 and see that the difference in the resistance is not substantial then, in all likelihood it will adjust its aspiration to a_2. Of course the opposite might happen if the difference is large and the initial aspiration was a_2.

Given now the prior probabilities $p_j'(c)$ that a country (c) will have aspiration a_j and the conditional probabilities $p_{ji}(s,c)$ that a country (c) having adopted system (s) and having prior aspiration a_j will end up with capability a_i, the <u>unconditional</u> probability $p_i''(s,c)$ that the country will achieve a_i is given by

$$p_i''(s,c) = \sum_{j=0}^{3} p_j'(c)p_{ji}(s,c) \qquad \text{(IV.14)}$$

To demonstrate how these unconditional probabilities of achievement can be estimated in practice, we assessed them for Country B of our example, and for the four sets of conditions discussed in Sections IV.6.1 and IV.6.2. To facilitate the calculations, we generated Tables IV.21 to IV.24, one for each set of conditions. The first column of each table specifies the possible weapons levels while the second column contains estimates of the prior probabilities of aspiration, i.e., the probability that the country in question has a particular aspiration regardless of which system is adopted. Thus, after examining the geographic and economic situation of Country B, the rivalries in its region as well as its ambitions, we might assess that there is a 40% chance that this country does not desire nuclear weapons and 60% that it does. Furthermore, we assess that given that this country wants nuclear weapons, there is an even chance of wanting a crude explosive or weapons of military quality. Hence, the prior probabilities for aspiration a_0, a_1 and a_2 are .40, .30, and .30 respectively, and are given in the second column of Table IV.21. The next columns of Table IV.21 contain the conditional probabilities of achievement for the various systems. Since we have considered three aspirations there are three columns for each alternative system. For example, for the assessment of conditional probabilities p_{0i} we assume that even if country B does not initially desire nuclear weapons (aspiration a_0), it might change its mind and try to obtain a weapons capability after adopting system I and examining the resistances of this system to the various aspirations. Thus, by examining the resistances of system I to the aspirations a_1 and a_2 -- as they are expressed in terms of the five attributes in Table IV.13 -- we assess that, conditional on the fact that initially country B did not desire nuclear weapons, the probabilities that the end result after adopting system I will be no weapons, crude explosive or 10 weapons of military quality are 65%, 10% and 25% respectively. Similar assessments were made for the other two possible initial aspirations (a_1 & a_2). These probabilities along with the corresponding probabilities for systems II to IV are given in Table IV.21. (The rationale behind some of these assessments is discussed later in this section.) Here, it was assumed that decision makers and experts directly assess the conditional probabilities of achievement by perusing Table IV.13. There are, however, procedures for assessing these probabilities by explicitly considering the contribution of each proliferation resistance attribute.

Once the prior and the conditional probabilities are assessed, the unconditional probabilities of achievement can be derived from Eq IV.14. In Table IV.21 the unconditional probability of achieving a_i (i=0,1,2) for a given system, is the last entry in the corresponding column.

We can now use the unconditional probabilities of achieving a particular weapons capability as a measure of the proliferation resistance -- for the corresponding aspiration -- of an alternative system. For example, under a "business as usual" environment and with relatively small difficulty in design and construction of a_2-weapons with RG-Pu, examination of the unconditional probabilities of achieving aspiration a_2 for the various systems, reveals the following ranking in terms of decreasing resistance (Table IV.21): System IV (.465) -- Systems I and II (.505) -- System III (.585). The corresponding ranking for aspiration a_1 is: System III (.145) -- Systems I and (II) (.175) System IV (.230). These orderings differ from the ones derived in Section IV.7 and given in Table IV.17 for the following reason. In section IV.7 the comparison was made for a given aspiration using as the only criterion the resistance of the system to the particular aspiration. In this section, however, we were able -- via the use of probabilities -- to allow for interactions between the aspirations and the corresponding resistances. Thus, if the difficulty associated with the use of R.G-Pu as a weapons material is small, the difference in the resistance of systems I-to-III to aspirations a_1 and a_2 is so insignificant (see Tables IV.13 & IV.15) that we assumed that if the would-be proliferator decides to construct nuclear weapons he would rather try for a_2 regardless of his initial intentions. This is probably even more characteristic of "crisis" environment than for a "business-as-usual" environment. For this reason, and because the resistance of system III is smaller than that of systems I and II (for both aspirations) it is more likely for system III that capability a_2 will be achieved instead of a_1, than it is for systems I and II.

This procedure of assessing the relative resistance of the alternatives systems for the various aspirations enables us to consider another "dimension" of their overall resistance, namely, the tendency of a system to shift the would-be proliferator to higher or lower aspirations. The "shifting" of the aspirations that an alternative system causes, along with the relative importance of the aspirations provides a measure of its overall resistance (for a given country). Thus in comparing systems I and III we note that a (.40, .30, .30) distribution of prior aspiration probability is transformed into (.320, .175, .505) by system I and into (.250, .145, .585) by system III (see Table IV.21). By assigning a relative weight (or utility) to each aspiration we could use the average weight (or expected utility) as a measure of the proliferation resistance of the system. More generally a utility could be assigned to each country/weapon capability pair, and then, by weighting these utilities with the corresponding unconditional probabilities of achievement, we can derive a measure of the proliferation resistance of an alternative system.

IV.9 Epilogue of Chapter IV.

Although in this chapter we went "all the way" and described how an overall ranking of alternative nuclear systems according to their proliferation can be achieved, there are good reasons for carrying the analysis to the point such that the final "product" are tables of the form of Tables IV.13 to IV.16, or at the most, tables giving the probability that a particular country will achieve various weapons objectives for different alternative systems. That is, in making a balance overall choice among possible nuclear systems, proliferation resistance is only one of many factors that must be considered; others are: (a) resource utilization, (b) economics, (c) safety, (d) environmental impacts, and (e) technological maturity. Thus, the output of a study of the proliferation resistance of alternative systems should not be in a form that allows only intercomparisons with respect to the proliferation resistance, but in a form that is compatible with judgements of other factors to form inputs for a broader study that will result in an "integrated" assessment of the alternative systems. We believe that output in the form of Tables IV.13 to IV.16 or in the form of similar tables containing probabilities of achievement in the place of the five attributes constitute such inputs.

TABLE IV.1

SYSTEM: LWR-Once Through-Reactors only- Light Sanctions

COUNTRY: B

N.W. ASPIRATION: Crude Nondeliverable Explosive

Pathway NO.	Pathway Description*	Development Time** (Years)	Warning Period †	Inherent Difficulty	Weapons Quality§	Cost ($M)
1	C-C-SF	2.0	4%	M/-	RG-Pu	20
2	C-O-SF	2.0	3%	M/-	RG-Pu	15
3	O-O-SF	1.5	6%	N/-	RG-Pu	25
4	C-C-FF	5.0	19%	-/H	HE-U235	270
5	C-O-FF	5.0	19%	-/H	HE-U235	250
6	O-O-FF	3.5	27%	-/H	HE-U235	330
7	I	4.0		L/-	WG-Pu	30
8						
9						
10						

* DESCRIPTION: Mode of Preparation-Mode of Diversion-Point of Diversion

C: Covert

O: Overt

SF: Spent Fuel

FF: Fresh Fuel

I: Independent of Alternative System

† Certainty Equivalent of Warning Time

** To First Device

§ HE U-233: Highly Enriched U-233

HE U-235: Highly Enriched U-235

RG-Pu: Reactor Grade Plutonium

WG-Pu: Weapons Grade Plutonium

TABLE IV.2

SYSTEM: LWR-Denatured Thorium-Reactors only-Light Sanctions

COUNTRY: B

N.W. ASPIRATION: a_1: Crude Nondeliverable Explosive

Pathway NO.	Pathway Description*	Development Time** (Years)	Warning Period †	Inherent Difficulty	Weapons Quality§	Cost ($M)
1	C-C-SF	2.0	4%	M/-	RG-Pu	25
2	C-O-SF	2.0	3%	M/-	RG-Pu	20
3	O-O-SF	1.5	6%	M/-	RG-Pu	30
4	C-C-SF	3.5	10%	M/H	HE-U233	50
5	C-O-SF	3.5	10%	M/H	HE-U233	40
6	O-O-SF	3.0	20%	M/H	HE-U233	60
7	C-C-FF	3.5	10%	L/H	HE-U233	90
8	C-O-FF	3.5	10%	L/H	HE-U233	80
9	O-O-FF	3.0	20%	L/H	HE-U233	110
10	I	4		L/-	WG-Pu	30

* DESCRIPTION: Mode of Preparation-Mode of Diversion-Point of Diversion

C: Covert

O: Overt

SF: Spent Fuel

FF: Fresh Fuel

I: Independent of Alternative System

† Certainty Equivalent of Warning Time

** To First Device

§ HE U-233: Highly Enriched U-233

HE U-235: Highly Enriched U-235

RG-Pu: Reactor Grade Plutonium

WG-Pu: Weapons Grade Plutonium

TABLE IV.3

SYSTEM: LWR-Pu-Recycle: Reactors only (PRE-IRR MOX)-Light Sanctions
COUNTRY: B

N.W. ASPIRATION: a_1: Crude explosive

Pathway NO.	Pathway Description	Development Time** (Years)	Warning Period †	Inherent Difficulty	Weapons Quality§	Cost ($M)
1	C-C-SF	2.0	4%	M/-	RG-Pu	20
2	C-O-SF	2.0	3%	M/-	RG-Pu	15
3	O-O-SF	1.5	6%	M/-	RG-Pu	25
4	C-C-FF	1.5	2%(2.18)	L/-	RG-Pu	10
5	C-O-FF	1.5	2%(1.7)	L/-	RG-Pu	10
6	O-O-FF	1.0	2%(2.3)	L/-	RG-Pu	10
7	C-C-FF	5.5	19%	-/H	HE-U235	300
8	C-O-FF	5.0	19%	-/H	HE-U235	300
9	O-O-FF	3.5	27%	-/H	HE-U235	350
10	I	4		L/-	WG-Pu	30

* DESCRIPTION: Mode of Preparation-Mode of Diversion-Point of Diversion

C: Covert

O: Overt

SF: Spent Fuel

FF: Fresh Fuel

I: Independent of Alternative System

† Certainty Equivalent of Warning Time

** To First Device

§HE U-233: Highly Enriched U-233

HE U-235: Highly Enriched U-235

RG-Pu: Reactor Grade Plutonium

WG-Pu: Weapons Grade Plutonium

TABLE IV.4

SYSTEM: LWR-Once Through Reactors only- Light Sanctions

COUNTRY: B

N.W. ASPIRATION: a_2: 10 weapons of military quality in a year

Pathway NO.	Description*	Development Time** (Years)	Warning Period †	Inherent Difficulty	Weapons Quality§	Cost ($M)
1	C-C-SF	2.5	4%	M/-	RG-Pu	30
2	C-O-SF	2.0	2%	M/-	RG-Pu	25
3	O-O-SF	1.5	3%	M/-	RG-Pu	40
4	C-C-FF	5.5	16%	-/H	HE-U235	400
5	C-O-FF	5.5	14%	-/H	HE-U235	350
6	O-O-FF	4.0	20%	-/H	HE-U235	480
7	I	6.0††		L/-	WG-Pu	90
8						
9						
10						

* DESCRIPTION: Mode of Preparation-Mode of Diversion-Point of Diversion

C: Covert

O: Overt

SF: Spent Fuel

FF: Fresh Fuel

I: Independent of Alternative System

† Certainty Equivalent of Warning Time

†† To Completion of Arsenal

** To First Device

§ HE U-233: Highly Enriched U-233

HE U-235: Highly Enriched U-235

RG-Pu: Reactor Grade Plutonium

WG-Pu: Weapons Grade Plutonium

TABLE IV.5

SYSTEM: LWR-Denatured Thorium-Reactors Only-Light Sanctions

COUNTRY: B

N.W. ASPIRATION: a_2:10 weapons of military quality in a year

Pathway NO.	Pathway Descrip-tion	Development Time** (Years)	Warning Period †	Inherent Difficulty	Weapons Quality§	Cost ($M)
1	C-C-SF	2.5	.10	M/-	RG-Pu	40
2	C-0-SF	2.5	.02	M/-	RG-Pu	30
3	0-0-SF	1.5	.03	M/-	RG-Pu	50
4	C-C-SF	4.0	.09	M/H	HE U-233	80
5	C-0-SF	4.0	.07	M/H	HE U-233	70
6	0-0-SF	3.0	.12	M/H	HE U-233	100
7	C-C-FF	4.0	.08	L/H	HE U-233	140
8	C-0-FF	4.0	.07	L/H	HE U-233	130
9	0-0-FF	3.0	.12	L/H	HE U-233	160
10	I	6.0††		L/-	WG-Pu	90

* DESCRIPTION: Mode of Preparation-Mode of Diversion-Point of Diversion

C: Covert

O: Overt

SF: Spent Fuel

FF: Fresh Fuel

I: Independent of Alternative System

† Certainty Equivalent of Warning Time

†† To Completion of Arsenal

** To First Device

§HE U-233: Highly Enriched U-233

HE U-235: Highly Enriched U-235

RG-Pu: Reactor Grade Plutonium

WG-Pu: Weapons Grade Plutonium

TABLE IV.6

SYSTEM: LWR-Pu-Recycle-Reactors only (Pre-IRR-MOX)
Light Sanctions
COUNTRY: B

N.W. ASPIRATION: a_2: 10 weapons of military quality in a year

Pathway NO.	Pathway Descrip-tion	Development Time** (Years)	Warning Period †	Inherent Difficulty	Weapons Quality§	Cost ($M)
1	C-C-SF	2.5	4%	M/-	RG-Pu	30
2	C-0-SF	2.0	2%	M/-	RG-Pu	25
3	0-0-SF	1.5	3%	M/-	RG-Pu	40
4	C-C-FF	1.5	0.5%	L/-	RG-Pu	25
5	C-0-FF	1.5	0.8%	L/-	RG-Pu	20
6	0-0-FF	1.0	1%	L/-	RG-Pu	30
7	C-C-FF	6.0	20%	L/H	HE-U235	520
8	C-0-FF	6.0	16%	L/H	HE-U235	470
9	0-0-FF	4.5	19%	L/H	HE-U235	580
10	I	6.0		L/-	WG-Pu	90

* DESCRIPTION: Mode of Preparation-Mode of Diversion-Point of Diversion

C: Covert

O: Overt

SF:Spent Fuel

FF:Fresh Fuel

I: Independent of Alternative System

† Certainty Equivalent of Warning Time

†† To Completion of Arsenal

** To First Device

§HE U-233: Highly Enriched U-233

HE U-235: Highly Enriched U-235

RG-Pu: Reactor Grade Plutonium

WG-Pu: Weapons Grade Plutonium

TABLE IV. 7

SYSTEM: LWR-Once Through-Reactors only- Light Sanctions

COUNTRY: C

N.W. ASPIRATION: a_1: crude nondeliverable explosive

Pathway NO.	Pathway Description	Development Time** (Years)	Warning Period †	Inherent Difficulty	Weapons Quality§	Cost ($M)
1	C-C-SF	2.5	9%	M/-	RG-Pu	25
2	C-O-SF	2.5	9%	M/-	RG-Pu	20
3	O-O-SF	2.0	17%	M/-	RG-Pu	25
4	C-C-FF	6.0	42%	-/H	HE-U235	280
5	C-O-FF	6.0	42%	-/H	HE-U235	280
6	O-O-FF	5.0	65%	-/H	HE-U235	330
7	I	5.0		L/-	WG-Pu	50
8						
9						
10						

* DESCRIPTION: Mode of Preparation-Mode of Diversion-Point of Diversion

C: Covert

O: Overt

SF: Spent Fuel

FF: Fresh Fuel

I: Independent of Alternative System

† Certainty Equivalent of Warning Time

** To First Device

§HE U-233: Highly Enriched U-233

HE U-235: Highly Enriched U-235

RG-Pu: Reactor Grade Plutonium

WG-Pu: Weapons Grade Plutonium

TABLE IV. 8

SYSTEM: LWR-Denatured Thorium-Reactors only-Light Sanctions

COUNTRY: C

N.W. ASPIRATION: a_1 : crude nondeliverable explosive

Pathway NO.	Pathway Descrip-tion	Development Time** (Years)	Warning Period †	Inherent Difficulty	Weapons Quality§	Cost ($M)
1	C-C-SF	2.5	10%	M/-	RG-Pu	35
2	C-0-SF	2.5	9%	M/-	RG-Pu	25
3	0-0-SF	2.0	17%	M/-	RG-Pu	40
4	C-C-SF	4.0	23%	M/H	HE-U233	60
5	C-0-SF	4.0	21%	M/H	HE-U233	50
6	0-0-SF	3.5	45%	M/H	HE-U233	70
7	C-C-FF	4.0	23%	L/H	HE-U233	80
8	C-0-FF	4.0	21%	L/H	HE-U233	70
9	0-0-FF	3.5	45%	L/H	HE-U233	90
10	I	5.0		L/-	WG-Pu	50

* DESCRIPTION: Mode of Preparation-Mode of Diversion-Point of Diversion

C: Covert

O: Overt

SF: Spent Fuel

FF: Fresh Fuel

I: Independent of Alternative System

† Certainty Equivalent of Warning Time

** To First Device

§ HE U-233: Highly Enriched U-233

HE U-235: Highly Enriched U-235

RG-Pu: Reactor Grade Plutonium

WG-Pu: Weapons Grade Plutonium

TABLE IV.9

SYSTEM: LWR-Pu Recycle: Reactors Only (Pre-Irr. Mox)
Light Sanctions
COUNTRY: C

N.W. ASPIRATION: a_1: Crude Explosive

Pathway NO.	Pathway Descrip-tion	Development Time** (Years)	Warning Period †	Inherent Difficulty	Weapons Quality§	Cost ($M)
1	C-C-SF	2.5	9%	M/-	RG-Pu	25
2	C-O-SF	2.5	9%	M/-	RG-Pu	20
3	O-O-SF	2.0	17%	M/-	RG-Pu	25
4	C-C-FF	2.0	6%	L/-	RG-Pu	15
5	C-O-FF	2.0	5.5%	L/-	RG-Pu	15
6	O-O-FF	1.5	10%	L/-	RG-Pu	15
7	C-C-FF	6.0	42%	-/H	RG-U233	300
8	C-O-FF	6.0	42%	-/H	HE-U233	300
9	O-O-FF	5.0	65%	-/H	HE-U233	350
10	I	5		L/-	WG-Pu	50

* DESCRIPTION: Mode of Preparation-Mode of Diversion-Point of Diversion

C: Covert

O: Overt

SF: Spent Fuel

FF: Fresh Fuel

I: Independent of Alternative System

† Certainty Equivalent of Warning Time

** To First Device

§ HE U-233: Highly Enriched U-233

HE U-235: Highly Enriched U-235

RG-Pu: Reactor Grade Plutonium

WG-Pu: Weapons Grade Plutonium

TABLE IV.10

SYSTEM: LWR-Once Through: Reactors only- Light Sanctions

COUNTRY: C

N.W. ASPIRATION: a_2: 100 weapons of military quality in a year

Pathway NO.	Pathway Description*	Development Time** (Years)	Warning Period †	Inherent Difficulty	Weapons Quality§	Cost ($M)
1	C-C-SF	3.0	8%	M/-	RG-Pu	40
2	C-0-SF	3.0	9%	M/-	RG-Pu	35
3	0-0-SF	2.5	19%	M/-	RG-Pu	50
4	C-C-SF	7.0	43%	-/H	HE-U235	470
5	C-0-FF	7.0	11%	-/H	HE-U235	400
6	0-0-FF	5.5	66%	-/H	HE-U235	530
7	I	7††		L/-	WG-Pu	110
8						
9						
10						

* DESCRIPTION: Mode of Preparation-Mode of Diversion-Point of Diversion

C: Covert

O: Overt

SF: Spent Fuel

FF: Fresh Fuel

I: Independent of Alternative System

† Certainty Equivalent of Warning Time

†† To Completion of Arsenal

** To First Device

§HE U-233: Highly Enriched U-233

HE U-235: Highly Enriched U-235

RG-Pu: Reactor Grade Plutonium

WG-Pu: Weapons Grade Plutonium

TABLE IV. 11

SYSTEM: LWR-Denatured Thorium-Reactors Only- Light Sanctions

COUNTRY: C

N.W. ASPIRATION: a_2: 10 weapons of military quality in a year

Pathway NO.	Pathway Description*	Development Time** (Years)	Warning Period †	Inherent Difficulty	Weapons Quality§	Cost ($M)
1	C-C-SF	3.0	17%	M/-	RG-Pu	55
2	C-O-SF	3.0	9%	M/-	RG-Pu	45
3	O-O-SF	2.5	19%	M/-	RG-Pu	60
4	C-C-SF	5.0	24%	M/H	HE-U233	100
5	C-O-SF	5.0	24%	M/H	HE-U233	90
6	O-O-SF	4.0	43%	M/H	HE-U233	120
7	C-C-FF	5.0	24%	L/H	HE-U233	160
8	C-O-FF	5.0	24%	L/H	HE-U233	150
9	O-O-FF	4.0	42%	L/H	HE-U233	180
10	I	7 ††		L/-	WG-Pu	110

* DESCRIPTION: Mode of Preparation-Mode of Diversion-Point of Diversion

C: Covert

O: Overt

SF: Spent Fuel

FF: Fresh Fuel

I: Independent of Alternative System

† Certainty Equivalent of Warning Time

†† To Completion of Arsenal

** To First Device

§HE U-233: Highly Enriched U-233

HE U-235: Highly Enriched U-235

RG-Pu: Reactor Grade Plutonium

WG-Pu: Weapons Grade Plutonium

TABLE IV.12

SYSTEM: LWR-Pu Recycle: Reactors Only (PRE-IRR.MOX)
Light Sanctions
COUNTRY: C

N.W. ASPIRATION: a_2: 10 weapons of military quality in 1 year

Pathway NO.	Pathway Description*	Development Time** (Years)	Warning Period †	Inherent Difficulty	Weapons Quality§	Cost ($M)
1	C-C-SF	3.0	8%	M/-	RG-Pu	40
2	C-0-SF	3.0	9%	M/-	RG-Pu	35
3	0-0-SF	2.5	19%	M/-	RG-Pu	50
4	C-C-FF	2.0	3.5%	L/-	RG-Pu	30
5	C-0-FF	2.0	4%	L/-	RG-Pu	25
6	0-0-FF	1.5	7%	L/-	RG-Pu	35
7	C-C-FF	7.5	44%	-/H	HE-U235	600
8	C-0-FF	7.5	42%	-/H	HE-U235	520
9	0-0-FF	5.5	66%	-/H	HE-U235	680
10	I	7††		L/-	WG-Pu	110

* DESCRIPTION: Mode of Preparation-Mode of Diversion-Point of Diversion

C: Covert

O: Overt

SF: Spent Fuel

FF: Fresh Fuel

I: Independent of Alternative System

† Certainty Equivalent of Warning Time

†† To Completion of Arsenal

** To First Device

§HE U-233: Highly Enriched U-233

HE U-235: Highly Enriched U-235

RG-Pu: Reactor Grade Plutonium

WG-Pu: Weapons Grade Plutonium

TABLE IV.13

Least Resistant Pathways For Given System, Country and Aspiration

Case I: "Business as Usual" Environment & "Small RG-Pu Difficulty"

COUNTRY		B										C									
ASPIRATION		a_1: Nondeliverable Crude Explosive					a_2: 10 weapons of Military Quality in 1 year					a_1: Nondeliverable Crude Explosive					a_2: 10 weapons of Military Quality in 1 year				
SYSTEM		D.T.	W.P.	I.D.	W.Q.	C	D.T.	W.P.	I.D.	W.Q.	C	D.T.	W.P.	I.D.	W.Q.	C	D.T.	W.P.	I.D.	W.Q.	C
I	LWR ONCE-THRU REACTORS ONLY	2.0	3%	M/-	RG-Pu	15	2.0	2%	M/-	RG-Pu	25	2.5	9%	M/-	RG-Pu	20	3.0	8%	M/-	RG-Pu	40
II	LWR DENATURED THORIUM REACTORS ONLY	2.0	3%	M/-	RG-Pu	20	2.0	2%	M/-	RG-Pu	30	2.5	9%	M/-	RG-Pu	25	3.0	9%	M/-	RG-Pu	45
III	LWR Pu-RECYCLE REACTORS ONLY	1.0	2%	L/-	RG-Pu	10	1.5	1%	L/-	RG-Pu	30	2.0	6%	L/-	RG-Pu	15	2.0	4%	L/-	RG-Pu	25
IV	INDEPENDENT PRODUCTION REACTOR	4.0		L/-	WG-Pu	30	6.0		L/-	WG-Pu	90	5.0		L/-	WG-Pu	50	7.0		L/-	WG-Pu	110

TABLE IV.14

Least Resistant Pathways For Given System, Country and Aspiration

Case II: "Business as Usual" Environment & "Large RG-Pu Difficulty"

COUNTRY		B										C									
ASPIRATION		a_1: Nondeliverable Crude Explosive					a_2: 10 weapons of Military Quality in 1 year					a_1: Nondeliverable Crude Explosive					a_2: 10 weapons of Military Quality in 1 year				
SYSTEM		D.T.	W.P.	I.D.	W.Q.	C	D.T.	W.P.	I.D.	W.Q.	C	D.T.	W.P.	I.D.	W.Q.	C	D.T.	W.P.	I.D.	W.Q.	C
I	LWR ONCE-THRU REACTORS ONLY	2.0	3%	M/-	RG-Pu	15	5.5	14%	-/M	HE-U235	350	2.5	9%	M/-	RG-Pu	20	7.0	41%	-/H	HE-U235	400
II	LWR DENATURED THORIUM REACTORS ONLY	2.0	3%	M/-	RG-Pu	20	4.0	7%	M/H	HE-U233	70	2.5	9%	M/-	RG-Pu	25	5.0	24%	M/H	HE-U233	90
III	LWR Pu-RECYCLE REACTORS ONLY	1.5	2%	L/-	RG-Pu	10	6.0	16%	-/H	HE-235	470	2.0	6%	L/-	RG-Pu	15	7.5	42%	-/H	HE-U235	520
IV	INDEPENDENT PRODUCTION REACTOR	4.0		L/-	WG-Pu	30	6.0		L/-	WG-Pu	90	5.0		L/-	WG-Pu	50	7.0		L/-	WG-Pu	110

TABLE IV.15

Least Resistant Pathways for Given System, Country and Aspiration

Case III: "Crisis" Environment & "Small RG-Pu: Difficulty"

COUNTRY		B										C									
ASPIRATION		a_1: Nondeliverable Crude Explosive					a_2: 10 weapons of Military Quality in 1 year					a_1: Nondeliverable Crude Explosive					a_2: 10 weapons of Military Quality in 1 year				
SYSTEM		D.T.	W.P.	I.D.	W.Q.	C	D.T.	W.P.	I.D.	W.Q.	C	D.T.	W.P.	I.D.	W.Q.	C	D.T.	W.P.	I.D.	W.Q.	C
I	LWR ONCE-THRU REACTORS ONLY	1.5	6%	M/-	RG-Pu	25	1.5	3%	M/-	RG-Pu	40	2.5	9%	M/-	RG-Pu	20	3.0	8%	M/-	RG-Pu	40
II	LWR DENATURED THORIUM REACTORS ONLY	1.5	6%	M/-	RG-Pu	30	1.5	3%	M/-	RG-Pu	50	2.5	9%	M/-	RG-Pu	25	3.0	9%	M/-	RG-Pu	45
III	LWR Pu-RECYCLE REACTORS ONLY	1.0	2%	L/-	RG-Pu	10	1.0	1%	L/-	RG-Pu	30	2.0	6%	M/-	RG-Pu	15	1.5	7%	L/-	RG-Pu	35
IV	INDEPENDENT PRODUCTION REACTOR	4.0		L/-	WG-Pu	30	6.0		L/-	WG-Pu	90	5.0		L/-	WG-Pu	50	7.0		L/-	WG-Pu	110

TABLE IV.16

Least Resistant Pathways for Given System, Country and Aspiration

Case IV:"Crisis" Environment & "Large RG-Pu Difficulty"

COUNTRY		B										C									
ASPIRATION		a_1: Nondeliverable Crude Explosive					a_2: 10 weapons of Military Quality in 1 year					a_1: Nondeliverable Crude Explosive					a_2: 10 weapons of Military Quality in 1 year				
SYSTEM		D.T.	W.P.	I.D.	W.Q.	C	D.T.	W.P.	I.D.	W.Q.	C	D.T.	W.P.	I.D.	W.Q.	C	D.T.	W.P.	I.D.	W.Q.	C
I	LWR ONCE-THRU REACTORS ONLY	1.5	6%	M/-	RG-Pu	25	4.0	20%	-/H	U235	480	2.5	9%	M/-	RG-Pu	20	5.5	66%	-/H	U235	530
II	LWR DENATURED THORIUM REACTORS ONLY	1.5	6%	M/-	RG-Pu	30	3.0	12%	M/H	U233	100	2.5	9%	M/-	RG-Pu	25	4.0	43%	M/H	U233	120
III	LWR Pu-RECYCLE REACTORS ONLY	1.0	2%	L/-	RG-Pu	10	4.5	19%	-/H	U235	580	2.0	6%	L/-	RG-Pu	15	5.5	66%	-/H	U235	680
IV	INDEPENDENT PRODUCTION REACTOR	4.0		L/-	WG-Pu	30	6.0		L/-	WG-Pu	90	5.0		L/-	WG-Pu	50	7.0		L/-	WG-Pu	110

TABLE IV.17

Case I: Ordering of alternative systems in terms of decreasing proliferation resistance. "Business as usual" environment and difficulty in design and construction of a_2 weapons with RG-Pu relatively small.

COUNTRY		B		C		B	C	OVERALL
	SYSTEM	ASPIRATION		ASPIRATION		ACROSS	ACROSS	RANKING
		a_1	a_2	a_1	a_2	ASPIRATION	ASPIRATION	
I	LWR once-thru	2	2	2	2	2	2	2
II	Denatured Thorium	1(~2)	1(~2)	1(~2)	1(~2)	1(~2)	1(~)	1(~2)
III	Pu-Recycle	4	4	4	4	4	4	4
IV	Production Reactor	3	3	3	3	3	3	3

TABLE IV.18

Case II: Ordering of alternative systems in terms of decreasing proliferation resistance. "Business as usual" environment and difficulty in designing and constructing a_2 weapons with RG-Pu relatively large.

COUNTRY		B		C		B	C	OVERALL
	SYSTEM	ASPIRATION		ASPIRATION		ACROSS	ACROSS	
		a_1	a_2	a_1	a_2	ASPIRATION	ASPIRATION	RANKING
I	LWR Once-thru	2	2	2	2	2	2	2
II	Denatured Thorium	1(~2)	3	1(~2)	3	3	3	3
III	Pu-Recycle	4	1	4	1	1	1	1
IV	Production Reactor	3	4	3	4	4	4	4

TABLE IV.19

Case III: Ordering of alternative systems in terms of decreasing proliferation resistance. "Crisis" environment and difficulty in designing and constructing of a_2-weapons with RG-Pu relatively small.

	SYSTEM	B ASPIRATION a_1	B ASPIRATION a_2	C ASPIRATION a_1	C ASPIRATION a_2	B ACROSS ASPIRATION	C ACROSS ASPIRATION	OVERALL RANKING
I	LWR once-thru	3	3	3	3	3	3	3
II	Denatured Thorium	2(∿3)	2(∿3)	2(∿3)	2(∿3)	2(∿3)	2(∿3)	2(∿3)
III	Pu-Recycle	4	4	4	4	4	4	4
IV	Production Reactor	1	1	1	1	1	1	1

TABLE IV.20

Case IV: Ordering of alternative systems in terms of decreasing proliferation resistance. "Crisis" environment and difficulty in designing and constructing of a_2 - weapons with RG-Pu relatively large.

	SYSTEM	B ASPIRATION a_1	B ASPIRATION a_2	C ASPIRATION a_1	C ASPIRATION a_2	B ACROSS ASPIRATION	C ACROSS ASPIRATION	OVERALL RANKING
I	LWR Once-thru	3	2	3	2	2	2	2
II	Denatured Thorium	2(∿3)	4	2(∿3)	4	4	4	4
III	Pu-Recycle	4	1	4	1	1	1	1
IV	Production Reactor	1	3	1	3	3	3	3

TABLE IV.21

Conditional and Unconditional Probabilities of Achievement for Country B.
CaseI: "Business as usual" Environment & "Small RG-Pu Difficulty"

WEAPONS LEVEL	PRIOR PROB. OF ASPIRATION	CONDITIONAL PROBABILITY OF ACHIEVEMENT GIVEN ASPIRATION											
		SYSTEM											
		I			II			III			IV		
		a_0	a_1	a_2	a_0	a_1	a_2	a_0	a_1	a_2	a_0	a_1	a_2
a_0	.40	.65	.10	.25	.65	.10	.25	.55	.10	.30	.65	.20	.15
a_1	.30	.10	.30	.60	.10	.30	.60	.05	.25	.70	.10	.35	.55
a_2	.30	.10	.15	.75	.10	.15	.75	.05	.10	.85	.05	.15	.80
UNCONDITIONAL PROBABILITY OF ACHIEVEMENT		.320	.175	.505	.320	.175	.505	.250	.145	.535	.305	.230	.465

TABLE IV.22

Conditional and Unconditional Probabilities of Achievement for Country B
CaseII: "Business as usual" Environment & "Large RG-Pu Difficulty"

WEAPONS LEVEL	PRIOR PROB. OF ASPIRATION	CONDITIONAL PROBABILITY OF ACHIEVEMENT GIVEN ASPIRATION											
		SYSTEM											
		I			II			III			IV		
		a_0	a_1	a_2	a_0	a_1	a_2	a_0	a_1	a_2	a_0	a_1	a_2
a_0	.40	.70	.25	.05	.65	.25	.10	.70	.25	.05	.65	.20	.15
a_1	.30	.10	.80	.10	.10	.70	.20	.10	.85	.05	.10	.35	.55
a_2	.30	.20	.30	.50	.15	.20	.65	.10	.40	.50	.05	.15	.80
UNCONDITIONAL PROBABIL. OF ACHIEVEMENT		.370	.430	.200	.335	.370	.295	.340	.475	185	.305	.230	.465

TABLE IV.23

Conditional and Unconditional Probability of Achievement for Country B. Case III: "Crisis" Environment & "Small RG-Pu Difficulty"

WEAPONS LEVEL	PRIOR PROB. OF ASPIRATION	CONDITIONAL PROBABILITY OF ACHIEVEMENT GIVEN ASPIRATION											
		SYSTEM											
		I			II			III			IV		
		a_0	a_1	a_2	a_0	a_1	a_2	a_0	a_1	a_2	a_0	a_1	a_2
a_0	.20	.60	.10	.30	.60	.10	.30	.50	.10	.40	.60	.25	.15
a_1	.40	.10	.30	.60	.10	.30	.60	.05	.20	.75	.05	.40	.55
a_2	.40	.05	.20	.75	.05	.20	.75	.05	.05	.90	.05	.10	.85
UNCONDITIONAL PROBABILITY OF ACHIEVEMENT		.180	.220	.600	.180	.220	.600	.140	.120	.740	.160	.250	.590

TABLE IV.24

Conditional and Unconditional Probability of Achievement for Country B. Case IV: "Crisis Environment" & "Large RG-Pu Difficulty"

WEAPONS LEVEL	PRIOR PROB. of ASPIRATION	CONDITIONAL PROBABILITY OF											
		SYSTEM											
		I			II			III			IV		
		a_0	a_1	a_2	a_0	a_1	a_2	a_0	a_1	a_2	a_0	a_1	a_2
a_0	.20	.65	.30	.05	.60	.25	.15	.65	.30	.05	.60	.25	.15
a_1	.40	.10	.80	.10	.10	.65	.25	.10	.85	.05	.05	.40	.55
a_2	.40	.15	.25	.60	.10	.20	.70	.15	.30	.55	.05	.10	.85
UNCONDITIONAL PROBABILITY OF ACHIEVEMENT		.230	.480	.290	.200	.390	.410	.230	.520	.250	.160	.250	.590

CHAPTER V

THE CHOICE PROBLEM OF THE POTENTIAL PROLIFERATOR UNDER UNCERTAINTY

V.1 General Remarks

In the previous three chapters we saw how we could assess the proliferation resistance of a given alternative system for a given country with a given nuclear-weapons aspiration. First, we identify--for this system-country-aspiration combination-- the pathways that can lead to the acquisition of nuclear weapons. Next, each pathway is scored in the proliferation-resistance evaluators or attributes. The pathways are then ordered in terms of decreasing resistance, where the ordering is dictated by the preferences and value tradeoffs of the would-be proliferator country. Finally, the resistance of the pathway thus identified as being the least resistant, is considered to constitute the resistance of the alternative system for the given country-aspiration combination.

In this chapter we will argue, however, that the resistance assessed according to the procedure described above is not always the best measure of the differential vulnerability of alternative systems to the proliferation of nuclear weapons. In particular, since we cannot really predetermine the particular pathway that a potential proliferator will follow, the most logical procedure is to assess the probability with which the proliferator will follow each of a number of possible pathways. Taking this uncertainty into account, we can then compare the alternative systems with regard to their proliferation resistance. This chapter is organized as follows. In section V.2 we discuss why an uncertainty exists about the pathway that the proliferator will follow. In section V.3 we present a procedure for quantifying this uncertainty. Finally, in section V.4 we show how alternative systems can be compared taking these uncertainties into account.

V.2 Least Resistant Pathway Versus Other Pathways

The basic assumption of the "least-resistant pathway" approach is that the would-be proliferator will perform, before choosing a pathway, a complete rational analysis of the form described in Subsection IV.6. However, the historical record does not always support this assumption.[4] It has been argued that in the past proliferation efforts have often been "step-by-step" procedures carried along by "scientific-momentum", rather than clear-cut top-level governmental decisions implied by a rational analysis. We also must note that there have been cases in which countries decided on the question of nuclear weapons after a "rational" top level analysis although their approach differed from the approach suggested in the previous chapter. We cannot, therefore, assume that in the future all the proliferation-related decisions will exclusively follow from a careful rational analysis.

Let us suppose for the moment that a rational analysis does take place. Even in this case, how do we know if the would be proliferator is going to use the same proliferation-resistance attributes? And even if he does, is he going to consider the same pathways and assess the same attribute-scores for a given pathway? Finally, and above all, how sure are we that we know his preferences and value tradeoffs? All these are legitimate questions, and the "bottom line" is that we cannot guarantee that our "rational" analysis is going to be perfomed by a potential proliferator; indeed, an exact simulation of the decision-making process of any country is impossible in principle. Any analysis, however, should take into consideration the fact that exactly the same alternative system- technical characteristics, institutional constraints, sanctions etc.- may substantially change its resistance for countries that differ greatly in economic development, resource availability, industrial infrastructure,etc.

Furthermore, the utility of a proliferation assessment from "our" point of view can still be argued on the following basis. Let us assume that we have enough information about the "objective" facts of the problem (attribute scores), as well as about the "subjective" aspects (preferences and value tradeoffs), to assess the least-resistant pathway for a given system-country-aspiration combination. Then it can be argued that if the potential proliferator were "smart" enough to perform the correct analysis he would choose the same pathway. In this case, our judgment is correct in the sense that, if for any reason, he chooses another pathway we "know" that he is making a mistake. Are not we then, drawing the right conclusions since we have based our analysis on the "truly" least resistant pathway? Well, the answer is maybe. To see why, we examine the following example.

Let us consider two alternative systems: (a) Light-Water-Reactor once through (System I); and (b) Light-Water-Reactor Denatured Thorium cycle (system II). We assume that only two pathways exist for each system: F(front-end) and B (back-end). For simplicity we will also assume that for a given country with a given aspiration (a), a one-dimensional measure of the proliferation resistance can be determined. The resistances of the pathways are as shown in Figure V.1.

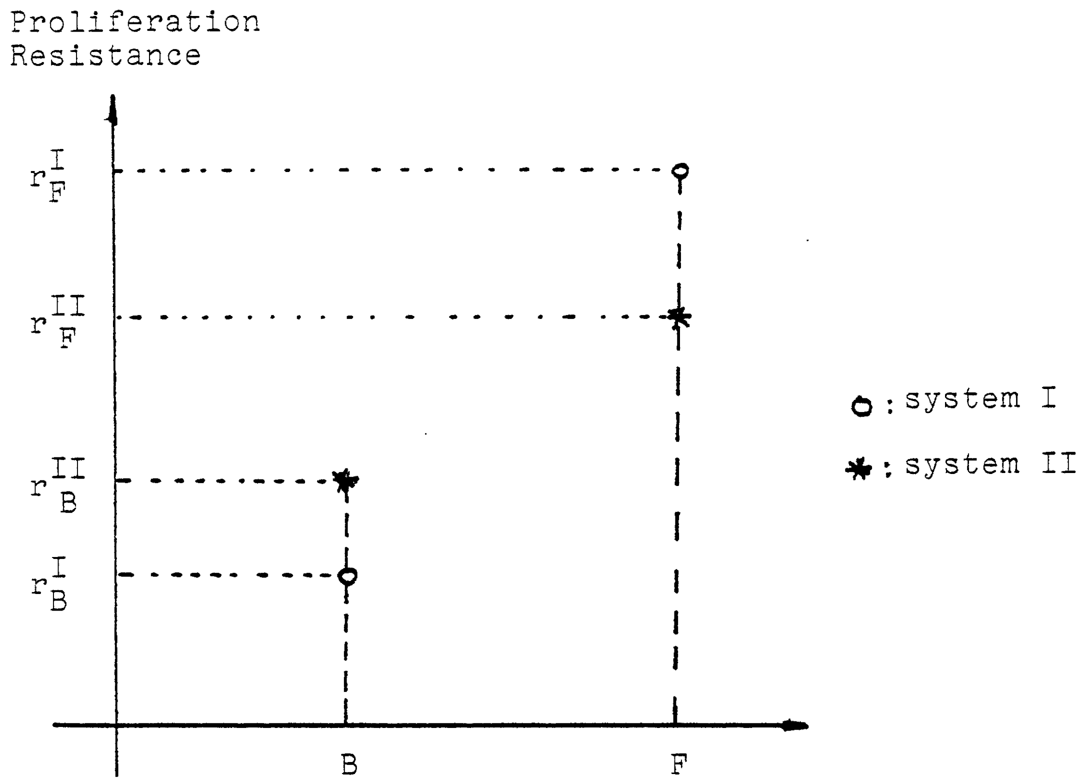

Figure V.1 Proliferation resistance of systems I,II.
System I: LWR-Once Through.
System II:LWR-Denatured Thorium

For this example a "rational" analysis from the viewpoint of the non-proliferation community would go as follows:

(1) If system I is adopted, country X, after performing a rational analysis, will attempt to attain a nuclear capability via pathway B-- the least resistant. Thus, system I is characterized by the resistance of this pathway, i.e., r_B^I

(2) Using a similar argument we characterize system II by the resistance of pathway B, i.e., r_B^{II}.

(3) Comparing the two systems, we note that $r_B^{II} > r_B^{I}$ and thus, we conclude that for country X having aspiration (a) system II is more resistant than system I.

If for a moment we assume that we are interested only in country X then we would recommend that system II should be adopted. Let us assume that system II is indeed adopted and country X tries to proliferate, but for some reason -- by "mistake" or because it is "forced" (19) to--it does so through pathway F and not B. Then, we see that we made the wrong decision by choosing system II because if we had chosen I it would have been much more difficult for country X to proliferate (see Figure V.1). Of course this would have not been the case if one or the systems "dominated" the other i.e., if it were more or at least equally resistant than the other in both pathways.

There are many reasons why a would-be proliferator might not follow the "least resistant" pathway as assessed by the procedure described in section IV.6. Any of the objections against "rational" approach qualifies as such a reason-- lack of rational analysis, different attributes, different preferences and value tradeoffs. Another major source of uncertainty is the fact that a proliferator might choose a particular pathway based on other criteria aside from proliferation resistance. For instance, "energy independence" might be such a criterion. That is, a proliferator might choose to proliferate through the front end of a nuclear cycle although it might be more resistant than the back end, because such a procedure provides a means of becoming "energy independent". The value of such an independence might lie both in its contribution to the mitigation of the consequences of possible sanctions as well as in other considerations that are well beyond the proliferation resistance regime.

Our basic conclusion is that we cannot use the information obtained from "rational" analysis as well as historical evidence in a deterministic way, i.e., to define a single least resistant pathway. We can, nevertheless, use such information in a probabilistic way. In other words we can, assess the relative likelihood or probability that a particular pathway will be followed. The comparison of two alternative systems with respect to their proliferation resistance becomes, therefore, a problem of choice under uncertainty.

In the following section (V.3) we outline how we could assess the probability that a given country will try to fulfill a nuclear weapons aspiration through a particular pathway. Next, in section V.4 we describe how we can use this information- i.e., the resistances of the pathways and the corresponding probabilities- in comparing two alternative systems.

V.3 Probability of choice of the i-th pathway

There are two possibilities which span the "choice-space" i.e., (a) that a careful "rational" analysis will precede the choice and (b) that such an analysis will not take place.

Let $\{i\}$,$\{L\}$, and $\{\bar{L}\}$ denote: the i-th pathway, that a rational analysis preceded the choice and that no such analysis was made, respectively. Then, the unconditional probability that the i-th pathway will be followed is given by

$$Pr\{i\} = Pr\{i\cdot(L+\bar{L})\} = Pr\{i\cdot L\} + Pr\{i\cdot\bar{L}\} \qquad (V.1)$$

since the events $\{i\cdot L\}$ and $\{i\cdot\bar{L}\}$ are mutually exclusive. Using the well known formula for the probability of a joint event $(A\cdot B)$ Eq. V.1 can be written as

$$Pr\{i\} = Pr\{L\}Pr\{i/L\} + Pr\{\bar{L}\}Pr\{i/\bar{L}\} \qquad (V.2)$$

where $Pr\{i/L\}$ and $Pr\{i/\bar{L}\}$ denote the conditional probabilities that the i-th pathway will be followed given that a rational analysis has taken place and that it has not, respectively. By virtue of Eq (V.2) it follows that if we know the three[20] probabilities $Pr\{L\}$, $Pr\{i/L\}$, and $Pr\{i/\bar{L}\}$, we can find the probability that the i-th pathway will be followed by the proliferator. The assessment of these probabilities is discussed in the following subsections.

V.3.1 Probability of Rational Analysis and Conditional Probability of Following the i-th Pathway

The probability that a particular country will perform a detailed analysis before choosing a proliferation pathway depends on many factors; e.g., the possibility of a crisis environment, involving regional rivals, the decision-making channels, and the structure and interrelation of the scientific political, and military bureaucracies. The assessment of this probability would carry us too far a field or our competence and interests. In general we would like to examine the sensitivity of the proliferation resistance of a system to changes in the value of this probability and thus we would like to treat it parametrically.

Once the assumption of a rational analysis is made, the analysis presented in Chapter IV (IV.1 to IV.6) is meaningful. For the reasons we mentioned in section V.2, however, we cannot conclude that the proliferator will follow the least-resistant pathway. We can, nevertheless, assess the probability that a particular pathway will be followed. Such a probability can be directly assessed by perusing tables that present the scores of the proliferation-resistance attributes for the various pathways (see for example Tables IV.1 to IV.12). These probabilities can be also assessed with the help of detailed quantitative analyses as the one presented in Appendix E. For example Pr {i/L} could be a function of the derived numerical composite score for the resistance value of the i-th pathway. Other more sophisticated techniques could also be used. We could consider, for example, value functions [21] that consist of a deterministic component and a random component; however, the description of such techniques is beyond the scope of this report.

V.3.2 <u>Probability of Following a Proliferation Pathway in the Absence of "Rational" Analysis</u>.

These probabilities depend basically on the observed frequency of the particular pathway i.e., on whether one or more of the countries that have proliferated in the past have rather limited data- six or so points-some sort of analysis will be alos necessary i.e., an examination of the political and military structure, the channels of power and control,etc. Such an assessment will be made by political scientists.

V.4 Proliferation Resistance Under Uncertainty

Once the uncertainties about the choice of the proliferation pathway are quantified as described in the previous section, the next step consists in assessing the resistance of the alternative system to the proliferation efforts of a country having a particular weapons objective. In this case, we don't have a single proliferation pathway to characterize the resistance of the system but rather a number of pathways each associated with a probability of being the one that characterize the alternative system. The possible "scores" of the attributes and the associated probabilities correspond to the attribute scores and probabilities of the possible proliferation pathways. Thus, in comparing the proliferation resistance of two systems for a given country and aspiration we have to compare two pathways for which the attributes are not deterministic variables but random variables. In doing so, we could apply the same procedure that we used for the attribute warning period. (see Section IV.5). According to this procedure we could establish a utility function for each attribute (from the non-proliferation coummunity point of view) and then determine a certainty equivalent for each attribute[22]. The proliferation resistance of the system is now represented by the resistance of this "composite" pathway consisting of the certainty-equivalents of the various attributes. From this point we can proceed with the analysis of section IV.7 or IV.8.

NOTES ON THE MAIN REPORT

1. This work builds on previous contributions dating from the start of the NASAP; we note in particular the work of Science Application Inc. ref. [1-2]

2. At this point we do not imply that the decision will be made in a consciously calculated, rational manner.

3. This is not our <u>only</u> aim since we recognize that we may be mistaken about our perceptions of his concerns and he may not act rationally even from his own "real" interests. See Chapter V.

4. It is recognized that sanctions might be applied after the completion of the weapons-objective. Here however, we are interested in the probability that sanctions will be applied before the completion of the weapons objective since it is this probability that might differentiate the pathways.

5. Such a mode of operation may indeed occur according to the scenario: [proliferation detection, followed by threat of sanctions, followed by pretention of compliance, followed by continuation of proliferation covertly], but is a possible dynamic response of the proliferator to a detection rather

than a preplanned way of operation (see also Appendix C on the utility of the working period). In any event, the exclusion of this mode does not affect the demonstration of the methodology.

6. Graphite-moderated air cooled reactor [7].

7. See Appendix A for details.

8. For this assessment we imagine ourselves in the position of the would-be proliferator.

9. In the following we will denote a pathway by $(x_1, x_2, x_3, x_4, x_5)$ where x_i is the level of the i-th attribute. The levels of the attributes for a particular pathway are given in Tables IV.1 to IV.12.

10. Although it might look difficult to obtain direct answers to questions of this sort, there are procedures for the systematic assessment of such indifference values (see also Appendix E). Very often an exact answer is not necessary and the simple determination of a region within which the indifference value lies (ball park figure) will suffice.

11. Here we refer to denatured Pu-239 with Pu-240 or Pu-238. For the latter case refer to Energy Daily Vol. 6 No. 142 July25, 1978.

12. More about such multiple representation will be found in Chapter V.

13. The numbers in Table IV.1 to IV.12 are partially based on preliminary assessments by S.A.I. [2].

14. See Chapter III & Appendix A.

15. Since it is likely that the sanctions will be different if the proliferation takes place through a system-dependent pathway than if through an "independent" one the utility of a particular warning period may be different for a dependent pathway than for an independent one. Comparisons of the certainty equivalents of the warning period corresponding to different utility functions do not make much sense, however, and hence other techniques should be employed. To avoid unnecessary complexity at this point we decided not to use the warning period when comparisons involving the independent pathway are involved.

16. For example, the Light Water Reactors are more vulnerable to fresh fuel supply curtailments than the Heavy Water Reactors. This difference although does not differentiate among pathways of a given system is important for system comparisons, i.e., comparisons of the least resistant path-

ways of the two systems.

17. Here we assume that the combined "resistance value" of the first four attributes of system I is higher or equal to that of system II.

18. This comparison is of course rather simplistic. In general, an increase in cost from $15 million to $20 million when the aspiration is a_1 has not the same value as a similar increase when the aspiration is a_2. Most probably the "value" of money will be less for aspiration a_2 than a_1. Such considerations should be kept in mind when we compare absolute differences in attribute "scores" across aspirations.

19. For example by removing the spent fuel outside the country immediately after its discharge from the reactors.

20. $\Pr\{\bar{L}\} = 1 - \Pr\{L\}$

21. See Appendices A and E.

22. This is an approximate method, however, since one of the conditions necessary for the use of certainty equivalents is not fulfilled (see Appendix A). The more powerful multi-attribute utility theory can be used in this case.

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