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Weapon Systems Requirements Analysis Employing a Hybrid of Analytic Technologies

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Prepared by
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Weapon Systems Requirements Analysis Employing a Hybrid of Analytic Technologies

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Abstract

A rigorous effort was made to apply professional systems engineering standards to the design of a modified Mk4 fuze. This required that, as systems engineers, we assess the system requirements from a force structure context in which the system is a single component of a strategic capability. This high level requirements analysis objective required the development of analytical capabilities that had previously not existed in a form suitable for design development efforts. The analysis that was conducted necessitated the development of a series of mission projections as well as a limited number of scenarios for which a strategic response might be required. These missions and stockpile projections provided a basis for assessing a subset of the total system requirements. The analyses also provide metrics in the mission dimension which could be used for concept development and system trade studies. The data permits designers and decision makers to identify the most cost effective solution to this design problem.

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Executive Summary

The Mk4/W76 is rapidly approaching it's original design service life. The result is an effort to bring the system in line with current technologies and define system requirements based on information that is not 20-30 years out of date. System requirements include, safety, cost, reliabilty, certifiability, dismantlemnt, as well as performance. The design problem is multi-criteria in nature, is not single issue, and requires information that can be used by decision makers to make the best concept selection for inclusion in the nation's strategic inventory.

The effort discribed in this document explores the subset of requirements, specifically the performance of the stockpile and the requirements of the Mk4/W76 component of the deployed stockpile. The effort required the development of an analytic capability to explore multiple stragetic configureations based on missions, targeting heuristics, operational scenarios, inventories, and system concepts. The capability developed is based on artificial life (A-life) concepts which proved to possess well matched capabilities. These analytic technologies included, fuzzy logic, evolutionary strategies, and an approximation to simulated annealing.

These analytic technologies had to be integrated to a number of classical techniques including, Taguchi analysis, multi-criteria decision making, scenario development, and target vulnerability calculations. Target vulnerabilties reflected overpressure, dynamic pressure, cratering and g-type targeting. The algoritms were based on Brode-Speicher correlations and on correlations found in PDCALC.

The requirements development focused on three basic sub-missions, START II projections(Series A in Table 1&4), START III scenarios(Series B in Table 1&4), and a number of strategic reserve force (SRF) missions. Within each of these three sub-missions variations in the independant variables were considered to capture uncertainties in projections. The independant variables included, operational status, mission, deployed inventories and mix, strategic reserve size, reliabiliites, mission success criteria, and new system configurations. Taguchi analysis techniques were used to identify the most stressing conditions for use in three confirmatory calculations used as the basis of the requirements assessments. The table which follows defines the results of the three confirmatory calculations. The information includes percentage of the mission assigned to the replacement SL system, the "normalized effective CEP" and the fraction of the mission employing a particular evolved fuze option.

Table 1: Confirmatory analysis results.

Series A 58%		Series B 39%		SRF 100%	
1.0	11%	1.0	6%	1.0	4%
1.8	4%	1.03	3%	2.5	96%
2.13	2%	1.79	4%		
2.23	1%	2.18	2%		
2.5	40%	2.5	24%		

Abstract. A rigorous effort was made to apply professional systems engineering standards to the design of a replacement fuze. This required that, as systems engineers, we assess the system requirements from a force structure context in which the system is a single component of a strategic capability. This high level requirements analysis objective required the development of analytical capabilities that had previously not existed in a form suitable for design development efforts. The analysis that was conducted necessitated the development of a series of mission projections as well as a limited number of scenarios for which a strategic response might be required. These missions and stockpile projections provided a basis for assessing a subset of the total system requirements. The analyses also provide metrics in the mission dimension which could be used for concept development and system trade studies. The data permits designers and decision makers to identify the most cost effective solution to this design problem.

The analytical hybrid developed employed a number of arti-

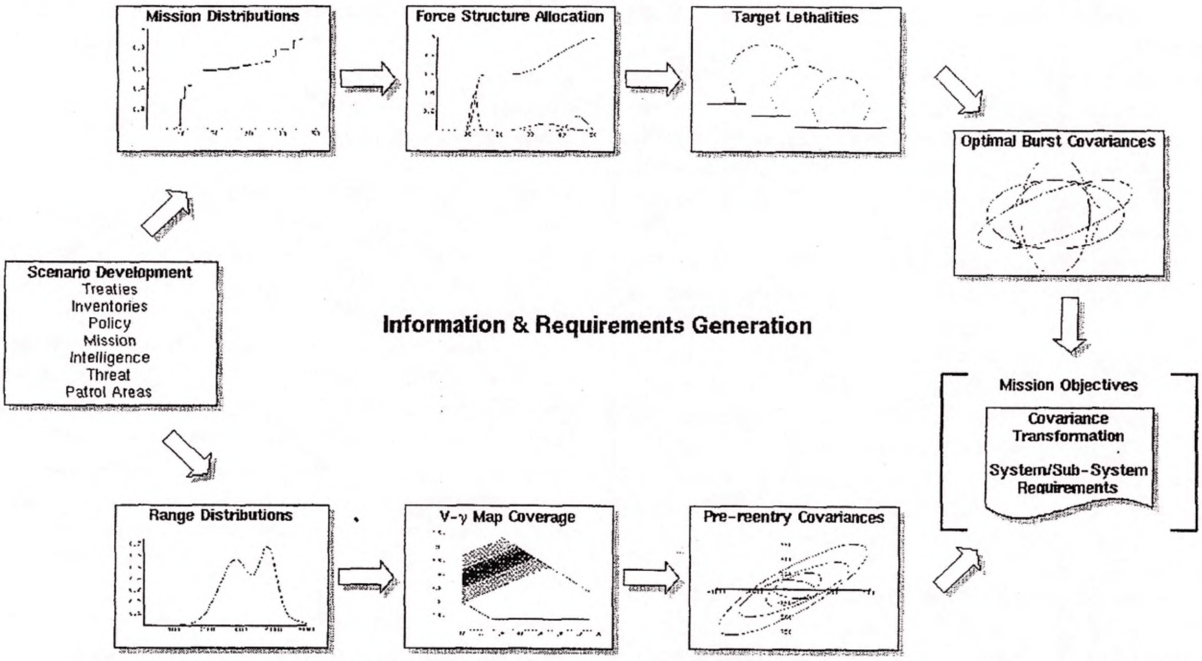

Figure 1. Mission analysis sub-process.

ficial life technologies as well as a convolution with fuzzy logic and multi-criteria decision making constructs. The problem associated with force structure analyses is the multi-dimensional character of the problem, as well as qualitative constraints which may be a product of the politics of strategic development. The mechanics of force structure analyses is a constrained multi-criteria optimization problem in which we are maximizing system performance on a strategic mission. The tools provide an ability to perform massive searches of concepts across a broad spectrum of missions in order to identify the most robust, effective solution to the constrained strategic force design problem.

The study explored a number of projections and explored scenarios associated with strategic reserve forces in the effort to identify a robust set of capabilities and avoid over specification which can result from system assessments in the absence of force structure considerations. The analyses were performed within a Taguchi framework in order to improve the efficiency of the calculations and provide insights into system sensitivities. Taguchi analysis is a design of experiment technique that has found favor in the commercial sectors. Precursor sensitivity calculations were performed to identify the most stressing conditions to be imposed on the replacement SL weapon system. These conditions were then used in sets of confirmatory calculations to identify the system requirements in terms of weapon system circular error probable (CEP) and associated weightings or the importance of an option requirement given mission parameters.

Introduction.

The suggested and actual service life of nuclear weapons ranges from 20 to 50 years depending on the system. The Mk4/W76 is reaching the end of design service life and as a result requires the attention and re-evaluation by the DoD and DOE design communities. The principle areas of emphasis are life extension issues and an increased nuclear safety margins comparable to the newer systems within the deployed stockpile. The measures of effectiveness (MOE's) for the system include cost, safety, mission, reliability, certification, retirement objectives, and the other "ilities" such as availability, maintainability, producibility, vulnerability, testability, etc. Mission effectiveness requirements pose a unique problem because of the necessity of identifying missions 30-50 years in the future, which represents the potential service life of the system. Projections of strategic systems missions, and operational environments have typically been less than 10 years. Design based on these projections could result in a system design that is obsolete at the time of system deployment. Uncertainties associated with future missions must be addressed by either, (1) flexibility of design, which can result in significant cost impacts to the customer or (2) as systems analysts we work to mitigate uncertainty of future missions.

Systems Engineering Analysis.

The analysis effort to support the development effort explores the transformation of mission needs to hardware concepts. Mission needs can be defined as distributions of targets in which the dimensions of the distribution include, geographic, clusterings, hardness or damage potential, areal extent, terrain features, and position uncertainty. Hardware concepts represent algorithms implemented in suites of sensors and processors which transform reentry uncertainties into pre-burst covariances which will result in suitable kills of mission targets. A simplified graphic of the development sub-process is depicted in figure 1. The force structure analysis provides the foundations for identification of range weighting distributions, target allocation distributions and associated target vulnerabilities. The range weightings allow us to identify sets of pre-reentry covariances to be used in developing optimal system transformations. These covariances represent the initial conditions for fuzing sub-system design. The target distributions, associated with a particular weapon systems mission, provide the final conditions. The system concept is the black box that transforms the initial conditions to the final pre-burst conditions.

Projections / Scenario Development. Projections and scenario development represent the initial activities needed to begin the systems analysis effort. Projections and scenarios generate information concerning strategic missions, inventories, and operational states for use in the development efforts. Projections, while accurate, lack the ability to anticipate discontinuous effects. These might be advances in technology, major political shifts, or common mode system failures. Projections can be characterized as extrapolations of trends observed in historical data. They can be extremely accurate for short term predictions. Scenarios, provide capabilities necessary for mission analysis efforts associated with systems requiring service lives on the oder of decades. Scenarios explore predictions from fundamental dynamic context. Predictions based on this approach might address global states from which problem specific questions are answered. For example, given a multi-polar high technology future what might a strategic mission against a central american adversary look like?

Weapon System Optimization. The mission profiles and weapon system inventories which result for the projections and scenario development effort are used as the basis for the weapon system optimization analyses. The objective is to identify one or more system configurations which when integrated into the existing deployed stockpile will compliment the inventories and not duplicate the other systems. Complementing and not duplicating capability has positive and negative connotations, a cost effective stockpile is one that mitigates duplication, while a reliable stockpile is one that may possess limited amounts of redundancy to mitigate effects resulting from common mode failures or delivery system survivability issues. The weapon to target allocation algorithms provide the basic fitness functions for use in the optimization efforts. Massive searches can be conducted in which system concepts are assessed within a force structure context to identify the most suitable solution to the design problem. The solution which best compliments the force structure during this phase of the studies leads to robust sets of system requirements.

Stochastic Covariance Transformations. The analysis effort identifies sets of pre-reentry conditions and covariances that characterize the initial conditions a weapon system must operate from. We also see that the final conditions are also represented by sets of conditions / covariances. The system design effort involves finding the transformation which can optimally transform the initial condition set into the final condition set. The constraints that are imposed in seeking this optimal transformation are based on the flexibility of the weapon system(sensor suites, aero-ballistic capability, etc.), and on the operational constraints (including information, preset accuracies, word lengths, delivery system accuracy, etc.) of the weapon and delivery system.

The search for this transformation is based on conventional design paradigms. A tool that could prove highly useful for this activity is the genetic programming approach being developed and used in a number of design arenas. This technology is founded in the evolutionary analytical sciences and is being used to design circuits, bridge trusses, and orbital control systems. The effort did not possess the resources or time to develop the unique operators for this type of genetic programming problem.

Concept Development. A basic conventional approach to design is being employed in the concept development activities. The optimization tools provide sets of effective CEPs which must be generated by the system hardware. The relationship between an effective CEP and probability of target kill is represented in the next equations.

$$Pk = 1.0 - 0.5^{\left(\frac{Wr}{CEP}\right)^2} \qquad \textit{Eqn. 1}$$

$$CEP_{eff} = \frac{Wr}{\sqrt{\frac{\ln(1.0-Pk)}{\ln(0.5)}}} \qquad \textit{Eqn. 2}$$

Concept development is achieved through a process of concept specification and transformation functionality. Comparisons between capability and objective identify suitable choices of concept architecture. Monti-Carlo techniques are employed to convolve burst covariances with target damage contours to identify system level probabilities of kill. This result is then compared to the system requirement (effective CEP) through the translations defined in equations 1 and 2. The process while not elegant has proven suitable for many generations of strategic system development.

Analytical Scope. A broad set of mission projections were proposed as well as scenario excursions developed in an effort to capture the mission requirements for this system. The system capabilities were assessed based on a system-of-systems context in which the Mk4 was considered to be part of a larger deployed nuclear stockpile. The delineation of the mission projections and the scenario projections provided a foundation from which weapon system optimizations could be conducted to identify the most suitable Mk4/W76 weapon system configuration. This approach differed from efforts in the past because it required analytical capabilities that have not existed within the DOE community. While the DoD community posses tools approaching the needed capabilities, the DoD algorithms are designed to provide detailed lay-downs and are ill suited for the studies needed to identify system requirements. The effort, therefore, required the development of tools which could be used to search for optimal configurations of the Mk4/W76 system under a broad spectrum of conditions. The tools needed to operate within a Taguchi framework, capture targeting heuristics, and facilitate multi-criteria decision problems. A brief description of these tools and the analytical framework follows in the next sections.

Taguchi Analyses.

Taguchi design techniques are employed in environments associated with non-linear complex systems and where engineers are concerned with achieving robust designs. The objective of robust design is to set design control parameters to target values that minimize response variability. Classical system response can be defined by the following relation.

$$y = f(M, x, z) \quad \textit{Eqn. 3}$$

M is the signal factor and defines external control of the system by an operator in order to attain some intended response values. x captures the noise characteristic of the system and environment which cannot be controlled by the system designer. Finally, z represents the control factors, the parameters that are under control of the designer to satisfy system requirements.

Taguchi techniques recognize that parameter design and tolerance design are two distinct approaches to robust design and there can be significant cost advantages associated with parameter design in non-linear systems. Robust or Taguchi design is founded on the premise that any deviation from a target value has a cost associated with it. The classic design margin approach assumes that all solutions within the design margins are equally acceptable. The next figure attempts to characterize this principle. When system cost is a function of response variability, a designer can work to reduce the uncertainties associated with the control factor, ie. tolerance design, or find a control factor target value that corresponds to a "flat" part of the response curve(shift of control from 75 to 175 in Figure 2).

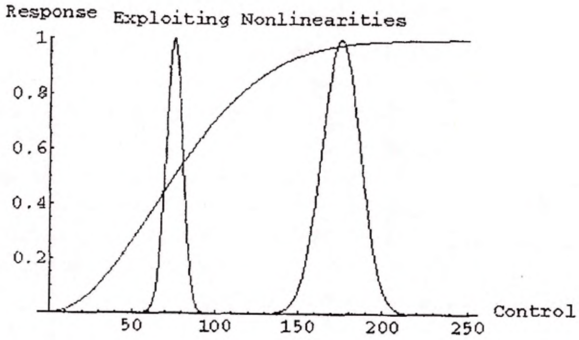

Figure 2. Generic application of robust design.

The techniques associated with these methodologies become highly useful for system analysis problems. The design problem being explored possesses a number of factors that must be addressed from a multi-criteria perspective in order to define system requirements. The sensitivity studies that are basic to the technique allow us to identify combinations of conditions that lead to the best design solution.

Sensitivity Analysis

A principle of Taguchi analysis is the identification of important design or analysis factors, usually in noisy environments. The analysis or experimentation that is typical of Taguchi methodologies provides information that can be used to optimize "level of effort" in design or analysis efforts. The process involves a parameter study to identify factors associated with the design problem and a noise analysis to define the characteristics of the operational environment. The control factor levels are set based on engineering judgement and constraints being imposed on the design problem. Once the parameter analysis is complete the technique requires a selection of an orthogonal matrix, the assignment of variables or parameters to the columns of the othogonal matrix, and the execution of analytical experiments. Subsequent to the experiments a statistical analysis is conducted to determine sensitivities, non-linearities, confounding effects etc. The experimental layout for a number of the analyses are included in the appendices.

Confirmatory Calculation. The preliminary sensitivity analyses used in these studies aided in the identification of the most stressing conditions being imposed on a replacement SL weapon system. For the purposes of the weapon system optimizations, we are attempting to identify the most system stressing conditions, and options that can provide the best performance under these conditions. The confirmatory calculation selects these conditions for use in a final calculation to determine the force configuration and system characteristics that best meets the needs of the customer.

Scenario / Projection Development.

There are two basic concepts for attempting to define environments a system may experience, the operational conditions that may be imposed and the functionality that may be assigned to a system in the future. The first, more basic approach is that defined as "projections". Projections are based on trend analyses. The second approach is "scenario development". In this case attempts are made to define a future environment and the system is then designed for functionality requirements in this postulated future.

Projections.

As indicated projections are based on trend analyses in which historical information is used to define conditions which will exist in the near future. Projections can possess high degrees of fidelity for these near term conditions but lack the ability to anticipate the unknown. Unknowns might be major political shifts and alliances, or major developments in technology.

A number of mission spectrums and stockpile inventories were identified and assessed in order to identify the effective CEP requirements for a replacement SL weapon system intended to compliment the deployed stockpile. The series A set of calculations, current and START II environments, involved pure projections based on treaty developments, operational trends, and target vulnerability trends.

Scenarios.

The series B set of calculations, START III, and the SRF missions were based on a limited scenario development approach. Environments were defined to capture inventories and target sets that might be evident in a future in which START III treaties were verified. The target sets used were based on projections of START II type mission spectrums. A more comprehensive scenario development effort would have included effort to define the composition of future target characteristics.

A great deal of consideration should be expended in an effort to capture future scenarios into which the replacement SL weapon system might be placed. The effort expended in this area will ultimately save the nation money since the system will possess the flexibility and robustness to deal with a broad spectrum of missions. Some of the considerations that may affect future missions include:

- Hardness trends
- Defensive weapon trends
- C4I projections
- Geo-political trend analysis
- New delivery platforms. Fast bomber fleet may impact requirements.

Weapon System Inventories. The inventories of weapon systems for the three analysis subsets are listed in table 4 of Appendix C. The inventories vary due to projections by different organizations and reflect the differing assumptions concerning possible treaty limits. The SRF inventories were assumed to consist solely of W76 weapons with varying quantities. This assumption was made to generate the most significant system performance demands.

Projected Missions. The current and START II experiments, Series A, explored three mission profiles. These are Scenarios A, B, and C in the experimental layout defined in the classified addendum. Scenarios D through G were estimates of possible mission profiles in a START III, or Series B, type environment. The target sets were generated statistically from extensive databases. The intent was to capture system needs and not to define or speculate on potential a adversaries and missions. Each experiment consisted of 1000 targets generated from statistical mission profiles. The the weapon system inventories were scaled from full target sets to the 1000 number to reflect or capture the implications of target rich and weapon rich environments.

The last four scenarios were used in the strategic reserve force (SRF) analyses and were designed to capture requirements which may arise due to third party belligerents. Again conditions were sought to develop requirements rather than plan an SRF mission. These cases were run against 500 targets per SRF scenario.

Analytical Architecture / Technologies.

The optimization algorithms are based on three major analytical elements, the system optimization routines, the target allocation routines, and a set of fuzzy logic routines.

Algorithm Structure

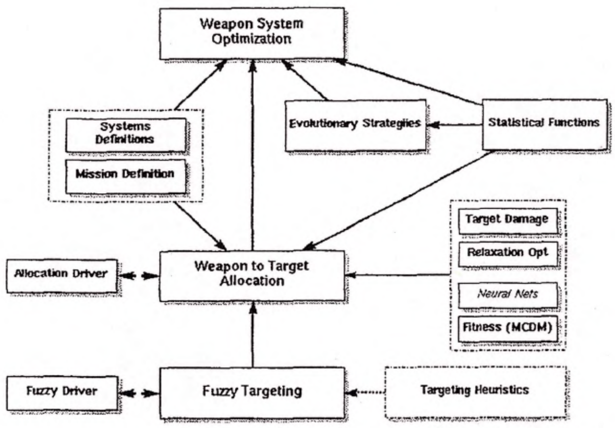

Figure 3. Basic algorithm structure.

The two major sub-blocks can be executed independent of the weapon optimization functions in stand-alone mode. This provides us with a higher degree of modularity and re-use as well as enhancing the validation and debug of the various algorithms. The targeting heuristics modeled in the fuzzy logic sub-component represents our best attempt to mimic the perceived targeting philosophy at strategic headquarters in an unclassified setting. The resultant rules could be significantly improved by obtaining a current allocation and using genetic programming principles to find an optimal set of rules reflecting current targeting philosophies.

Fuzzy Logic (Targeting).

Fuzzy set theory is an extension of classic set theory. In classic set theory component membership is defined by a Dirac Delta function, either 1 or 0. Fuzzy set theory allows set members to possess membership values which range continuously over the domain between 0.0 and 1.0. These membership functions provide us with an ability to characterize the degree to which an element might belong to a specified set. For example, given a set of "accurate weapons", a system possessing a CEP of "X" feet might possess a membership value of 0.5, while a system with a "10X" foot CEP has a membership value in the set of "accurate weapons" of 1.0e-9, reflecting a fact that in some scenarios even a "10X" CEP might be considered accurate. Unlike statistical concepts which consider the uncertainties associated with assessing an observable, fuzzy deals with the uncertainty associated with the underlying physics or functionality.

Fuzzy logic extends this unique set theory by defining the calculus that can be used to capture behavior in this problem space. This treatment of fundamental functional uncertainties provides us with another tool for modeling complex dynamics, and non-linear systems. Implementation of the calculus of fuzzy logic provides us with the ability to perform approximate reasoning. The dynamics of the system is captured by semantic rule sets operating on semantic variables. The multi-faceted nature of targeting, both deterministic and heuristic, requires a hybrid approach for which fuzzy logic is a good match.

Fuzzy provides us with the ability to model / approximate the highly complex problem of weapon system allocation in which many of the phenomena cannot be modeled deterministically. The politics, and psychology of strategic targeting can be easily modeled in linguistic rules but is impossible in closed form analytic form. Fuzzy also permits us to consider conflicting guidance in the allocation process. As directives evolve, allocation strategies may emerge which are in internal conflict. Unlike expert rule based systems which typically fail under these conditions, fuzzy logic can operate under these conditions flawlessly.

Fuzzification. Fuzzy modeling requires transformations between crisp and fuzzy domains in order to capture the dynamics of a system. The objectives of fuzzy models is to develop rule sets which operate on linguistic variables which in turn capture the dynamics of the process or system. Fuzzification is a process in which the concepts of numbers are re-represented in terms of fuzzy linguistic entities. Once the model representations are captured in this fuzzy linguistic space the operations or transformations defined by the rule set can be performed. The result of the fuzzy transformations is another set of linguistic fuzzy variables which must be transformed back into the real domain for evaluation. This process is de-fuzzification.

De-Fuzzification. After a rule set has been processed the resulting consequent set must be quantified. This process is called "de-fuzzification" in the literature (Cox, 1994). There are three methods that have been considered in these development efforts. They include: the centroid method, the average maximum method and the maximum method. The next figures provide a simple graphic of rule processing.

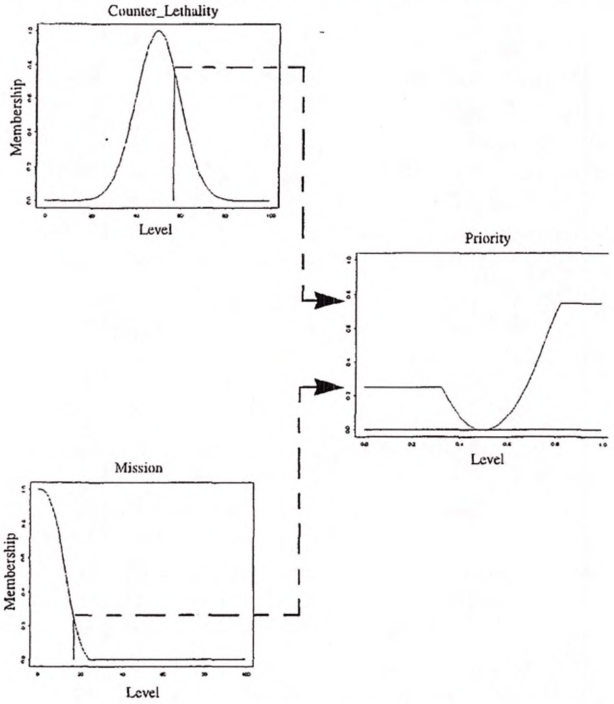

Figure 4. Graphic representation of rule processing.

Figure 4 graphically demonstrates the processing of a simple set of rules as defined below.

- if COUNTER_LETHALITY is MODERATE then PRIORITY is HIGH
- if MISSION is STRATEGIC_OFFENSE then PRIORITY is LOW

Assuming the value for COUNTER_LETHALITY was 57 and MISSION was 16.4. The lines between the charts reflect the degree of truth of the antecedents and the resulting impact on the consequent parameter, PRIORITY. The membership distribution for PRIORITY is represented by the two clipped sigmoid distributions. The average maximum de-fuzzification method would produce a priority result in the neighborhood of 0.9. The centroid method would produce a priority in the range of 0.6 to 0.8. The maximum method would result in either 0.8 or 1.0 depending on the version of the de-fuzzification method.

Fuzzy Targeting. In order to develop rules associated with weapon system targeting we were forced to redefine a coding system for the targets based on a three parameter model. The category code structure associated with strategic target sets represent a book keeping scheme, as opposed to a characteristic scale similar to a member of a fuzzy set. The raw category codes do not allow us to take advantage of the inherent strengths of fuzzy logic.

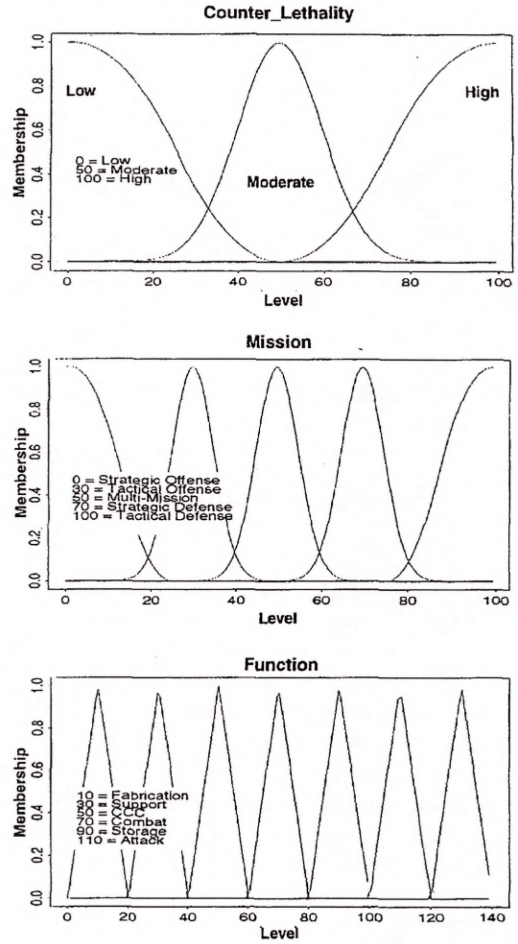

Figure 5. Membership functions for Mission, Function, and Counter_Lethality.

The independent variables selected include the following three parameters: Mission, Function, and Counter_Lethality. Associated with each variable is a set of levels. Levels act as units associated with the variable similar to the numbers which belong to the positive integer set. The levels associated with Mission include: strategic offense and defense, tactical offense and defense, and multi-missions. Counter_Lethality is comprised of low, moderate and high. Counter_Lethality in this context is the damage a surviving target could inflict on us. Finally, function consists of: fabrication, support, command & control, combat, storage, attack, and "weapons of mass destruction" (WMD) storage. The next figure depicts the variables and the membership functions for each level used in the studies.

The objective of the fuzzy targeting within this analytical architecture involves the assessment of target weighting, recommended detonation altitudes and strategic time line considerations associated with delivery system response times and survivability. The consequent fuzzy variables include: priority, timing and height of burst (HOB). The levels defined for priority include: High, moderate, and low. The levels of timing include: days, hours, and minutes. Finally, the levels of HOB include: high, moderate, low, and contact.

Hedges. Hedges represent mathematical adjectives in the arena of fuzzy logic. They are used as modifiers to semantic variables and act to change the distribution associated with the membership function. The membership function for "high" of the semantic variable counter_lethality can be modified by the hedge "very". The effect of that operation is a change in the membership function by squaring each point on the membership function. This results in a sharpening of the distribution function for "high".

The first cut at sets of fuzzy targeting rules are provided in

Table 2: Sample rule set used in the first strategic targeting studies.

Table 2: Sample rule set used in the first strategic targeting studies.

Rule No.	Rule
a1	< if FUNCTION is FABRICATION then HOB is HIGH >
a2	< if COUNTER_LETHALITY is HIGH and MISSION is STRAT_OFF then HOB is CONTACT >
a3	< if FUNCTION is SUPPORT then HOB is HIGH >
a4	< if FUNCTION is CCC then HOB is LOW >
a5	< then HOB is MODERATE >
b1	< if MISSION is STRAT_OFF then PRIORITY is VERY HIGH >
b2	< if MISSION is STRAT_DEF then PRIORITY is HIGH >
b3	<if MISSION is TAC_OFF then PRIORITY is SOME-WHAT HIGH>
b4	< if MISSION is TAC_DEF then PRIORITY is MODER-ATE >
b5	< if MISSION is MULTI_MIS then PRIORITY is VERY MODERATE >
b6	< if MISSION is TAC_DEF and FUNCTION is FABRI-CATION then PRIORITY is VERY LOW >
b7	< if MISSION is TAC_DEF and FUNCTION is STOR-AGE then PRIORITY is LOW >
b8	< if MISSION is TAC_OFF and FUNCTION is SUPPORT then PRIORITY is MODERATE >
b9	<if COUNTER_LETHALITY is VERY HIGH then PRI-ORITY is VERY HIGH >
b10	< if FUNCTION is SUPPORT then PRIORITY is LOW >
b11	< if FUNCTION is CCC then PRIORITY is MODERATE >
b12	< if FUNCTION is FABRICATION then PRIORITY is LOW >
b15	< if FUNCTION is ATTACK then PRIORITY is VERY HIGH >
b16	< if FUNCTION is WMD_STORAGE then PRIORITY is HIGH >
c1	< if COUNTER_LETHALITY is HIGH then TIMING is MINUTES >
c2	< if COUNTER_LETHALITY is MODERATE then TIM-ING is HOURS >
c3	< if COUNTER_LETHALITY is LOW then TIMING is DAYS >
c6	< if MISSION is STRAT_OFF then TIMING is MIN-UTES >
c7	< if MISSION is STRAT_DEF then TIMING is FEW MINUTES >
c8	< if MISSION is TAC_OFF then TIMING is HOURS >
c9	< if FUNCTION is FABRICATION then TIMING is DAYS >
c10	< if FUNCTION is SUPPORT then TIMING is HOURS >
c11	< if FUNCTION is CCC then TIMING is MINUTES >
c12	< if FUNCTION is COMBAT then TIMING is HOURS >
c13	< if FUNCTION is STORAGE then TIMING is DAYS >
c14	< if FUNCTION is ATTACK then TIMING is MINUTES >
c15	< if FUNCTION is WMD_STORAGE then TIMING is HOURS >

the table 2.

Appendix A contains tables defining the transformation between category codes, and the metrics used in the weapon system allocation code. As mentioned earlier, category codes are unsuitable for use in the fuzzy targeting models and had to be transformed into semantic variables that could be used by the rule set defined. The approach was to select roughly 80 plus category codes, transform them into the semantic space discussed and execute the rule base on these 80 plus target types to generate values for the HOB, priority, and timing variables which were used in the weapon system allocation portion of the analytic models.

The de-fuzzification method used to generate the table is the "centroid" de-fuzzification method. The average maximum and the maximum methods were explored, however, the centroid method appears to produce the best results for this application. The next couple of displays provide results of the rule set defined in table 2. Figure 6 provides a subset of information useful for assessing the suitability of the targeting rule base. The axes represent target accounting codes vesus the time urgency parameter.

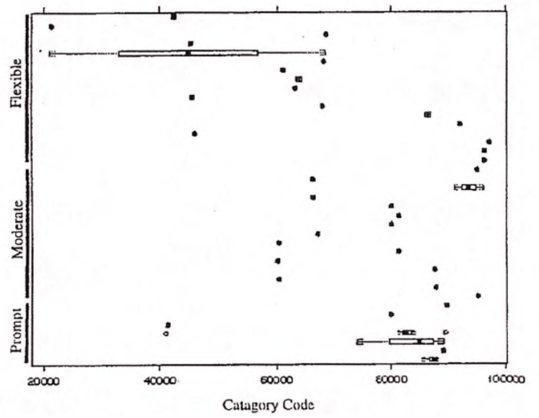

Figure 6. Target timing as a function of category code.

Figure 7 provides information which correlates target Counter_Lethality with the time urgency fuzzy variable. The trend identified is consistant with expectations, i.e. lethal targets should be attacked early in an a strategic operation.

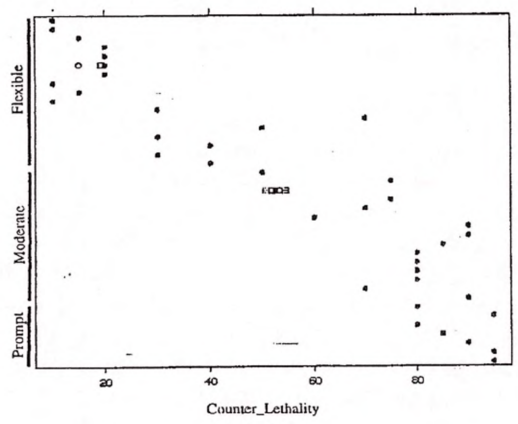

Figure 7. Target timing as a function of target Counter_Lethality.

Figures 8 and 9 provide information concerning the prioritization of targets. This dimension of the problem becomes important in target rich environments. In target rich environments the process involves an allocation of weapons to the targets starting with the highest priority (rank 1 in the charts) to the lowest priority. The "b" series of rules, the rules associated with priority, in table 1 were used to generate the following plots. The series of plots were used as part of a validation process. The objective was to capture, within the time frame of the analyses, a set of targeting heuristics that reflected actual targeting mechanics. Additional effort would be needed to add fidelity to the rule base as well as provide a foundation from which policy issues associated with strategic targeting could be explored.

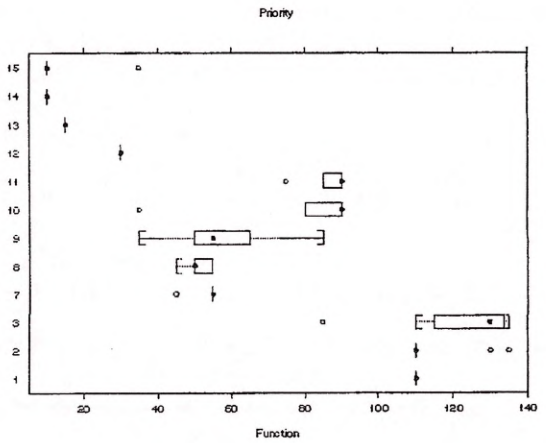

Figure 8. Target ranking by category code.

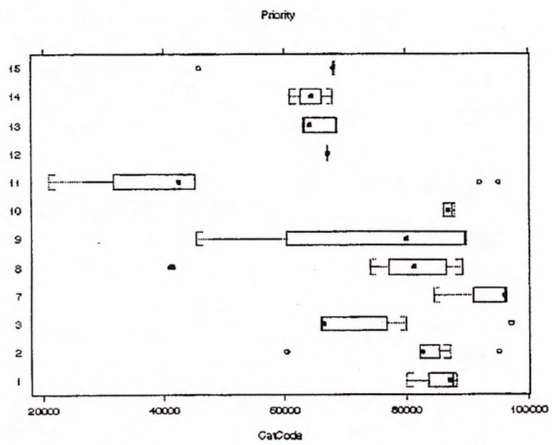

Figure 9. Target ranking by function.

Genetic Optimization (Weapon System Allocation).

The objective of the allocation algorithms is to select the best weapon for use against a target consistent with a set of criteria or objectives. A characteristic of this optimization problem is the multiple combinations of acceptable solutions. A graphical depiction of the problem is the generic representation of the optimization complexity provided in Figure 10 below. The axises are indicative of combinations of allocations and the resulting fitness of the mission. The point to be drawn from the figure is the complex response surface associated with weapon system allocation optimizations. The initial effort to find a solution algorithm was to use genetic algorithms with cyclic permutation operators. What became evident, and it should have been obvious on my part, was the inordinate amounts of computational effort required to find a solution. Genetic algorithm can be characterized as directed random searches for an optimal solution. The random aspects of the search on a complex response surface is mechanistically inefficient. The complexity associated with the optimization is in part due to the numerous combinations of optimal solutions and to fitness functions that are at a mission level. The importance of unit allocation changes using these fitness functions is averaged over the number of targets in the strategic mission. The result is minimal impact to mission fitness due to small changes in the allocation scheme.

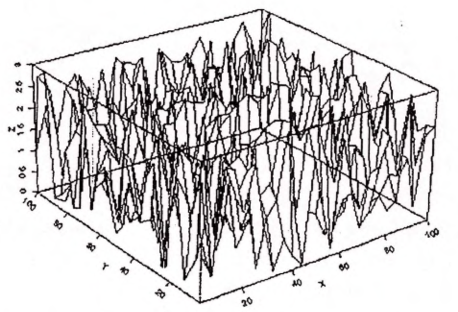

Figure 10. Response surface characteristic of a weapon system allocation problem.

The allocation solution methodology which proved to be the most efficient was based on a relaxation principle. The mechanics of this optimization technique involves a prescreen for sub-optimal weapon allocations in which suitability is defined by the user. Each sub-optimal solution is compared randomly to other sub-optimal solutions in this distribution, if mission fitness is improved by exchanging weapon allocations, the exchange proceeds otherwise the exchange of allocation does not occur. The pseudo code for the optimization is presented in the following table.

Table 3: Optimization Pseudo code.

```
Loop on all allocations
 {
 Compare allocation fitness to user defined acceptance
  If ( fitness < acceptance )
    Add to "unacceptable allocation distribution (UAD)"
 }
Loop on UAD distribution
 {
 randomly select another allocation from UAD
 exchange weapon allocations for the two targets
 if( fitness new > fitness old )
   make exchange permanent
 }
```

The fitness of an allocation is defined by sets of criteria to be discussed in the next section.

Multi-criteria Decision Analysis (Fitness Functions).

Strategic targeting represents a multi-dimensional optimization problem in which many of the criteria may possess qualitative foundations. Target priority is a clear example of a qualitative criteria. Policy directives, military objectives, and geo-political opinions all contribute to the dynamic of target prioritization. The following set of criteria was used in the force structure analysis documented in this note. The criteria consisted of the following 7 factors.

- Minimum Yield
- Objective probability of damage (Pd)
- Stockpile constraints
- Target importance
- Strategic time lines
- HOB objectives
- Control sub-system Reliability

The factors listed can be grouped into two basic types, those exhibiting threshold type behavior and those more appropriately characterized as goal functions. Threshold criteria drive the suitability of a weapon to target allocation to zero if the fitness threshold of the criteria is not reached. This is used to capture stockpile limits, if there are insufficient numbers of systems to cover targets, the fitness contribution for an uncovered target must be zero. With goal type criteria, such as objective Pd, credit is given for an allocation which produces a probability of target kill different from the mission goals. This characterization, while rather simple, captures the functionality of interest. Second order effects might drive certain targets to transition into threshold type criteria. Allocations failing to inflict a minimum level of damage, would be equivalent to an allocation which inflicts no target damage. The mission fitness correlation is defined in the next section and characterizations of a number of the fitness criteria are discussed in subsequent sections.

Mission Fitness Correlation. The functional form of the mission fitness function is presented in equation 4. The functionality captures threshold type criteria as well as goal type criteria.

$$F_{total} = F_{stk} \cdot F_{wt} \cdot F_{tm} \cdot F_{re} \cdot (F_{Pd} + F_h + F_y) \qquad \text{Eqn. 4}$$

In this expression F_{tm} is the fitness associated with strategic timing issues, F_{re} addresses system reliability, F_{Pd} captures objective Pd issues, F_h covers to height of burst considerations, and F_y represents minimum yield considerations. F_{stk} captures the stockpile fitness and is either 0 or 1 depending on the ability to allocate a weapon system to a given target. F_{wt} captures target weighting concerns. When there are sufficient numbers of weapons in the inventory the term takes on the priority of the target, the problem becomes one of maximizing the sub-fitness' for high priority targets in order to maximize mission fitness. The weighting parameters also act as a threshold in target rich environments. Under these conditions, a lower priority cutoff is established that corresponds to the number of higher priority targets that can be attacked.

The maximum mission fitness that is attainable is 3.0 and the minimum fitness is 0.0. Each sub-criteria of the mission fitness function can range in value from 0 to 1 with the summed terms in parentheses driving the maximum value.

Objective Probability of Damage. Figure 11 defines the functional form of the probability of damage fitness correlation. The peak of the curve occurs at a value defined as the objective Pd. The degradation in fitness for probabilities of damage below and above that value is founded on the logic that too much capability is as bad as too little damage capability. This effect shows up in the requirements for the weapon system. Fitness correlations that indicate "bigger is better" will drive the system requirements up and potentially impact cost.

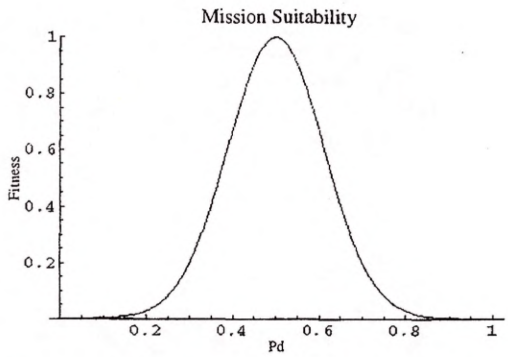

Figure 11. Objective probability of damage fitness function.

Minimum Yield. The functional form of this fitness criteria, Figure 12, had to capture the targeting objective of imposing the minimum yield available on the target while still satisfying the other criteria. This criteria has foundations in the desire to mitigate collateral damage in particular, and to preserve our most capable systems for allocations for more stressing problems.

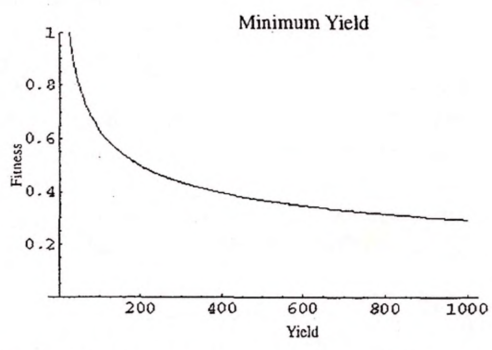

Figure 12. Fitness function for minimum yield constraints.

HOB objectives. The criteria associated with heights of burst (HOB) captures issues associated with optimal or recommended HOBs. Physics of weapons, targets, terrain, or trajectory can impose constraints on targeting HOB. This fitness function, Figure 13, captures the effect of this problem mathematically.

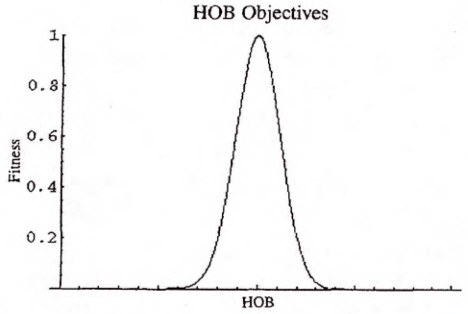

Figure 13. Fitness function for height of burst (HOB) preferences.

Strategic Time Line. Strategic time line is a decision metric associated with target attack urgency, system delivery times, and indirectly delivery system survivability. Target time urgency takes target counter_lethality into consideration when allocating weapon systems to the target. For example, strategic offense targets are a class of target that would be targeted early in a mission while strategic storage facilities, under most scenarios, could be targeted late in a mission. Survivability of the delivery system becomes a timing issue if there is some question of first strike survivability. These systems might be best suited for allocation to time urgent targets. The forms assumed for weapon system timing considerations are presented in Figure 14. These figures represent ICBMs, SLBMs, and air delivered systems. In conjunction with the fuzzy targeting model, which defines timing urgency, these generic delivery time curves provide a decision metric for proper assignment of system to target.

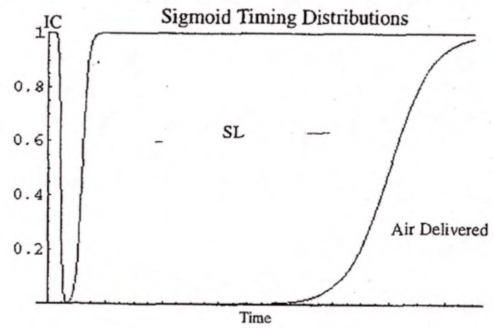

Figure 14. Delivery time characteristics for IC's, SL's and air delivered weapon systems using sigmoid functions.

Validation. Validation of the allocation model was conducted on a best guess of current targeting conditions and associated allocation rules.

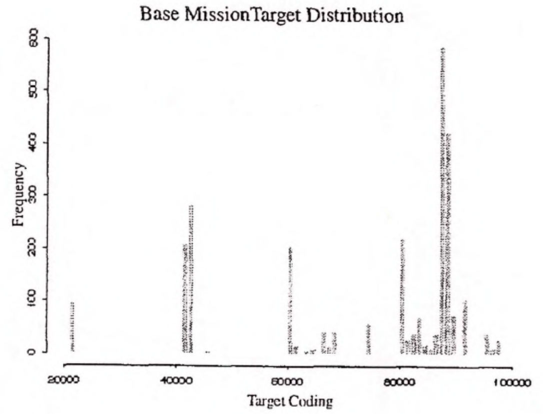

Figure 15. Target distribution for base mission.

Two sets of base mission allocations were performed. The first used response times for the air delivered assets such that 50% of the weapons could be delivered in 750 minutes. The second set of allocations set the mean delivery time to 1200 minutes. Figures 16 and 17 provides comparisons of a couple of target classes for the two response times.

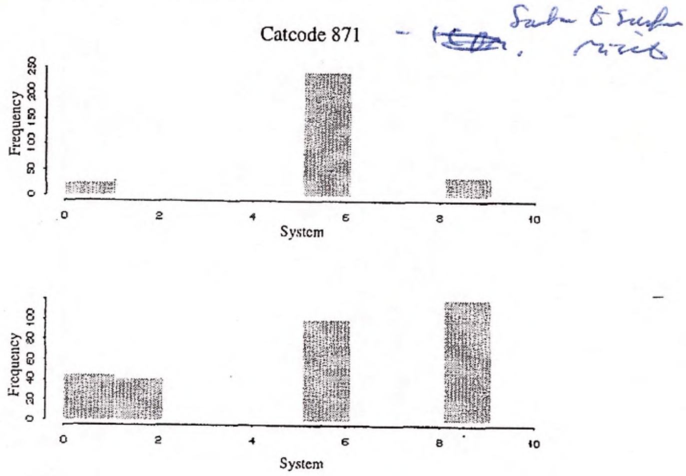

Figure 16. Allocations of weapons to target class 871 with different response times.

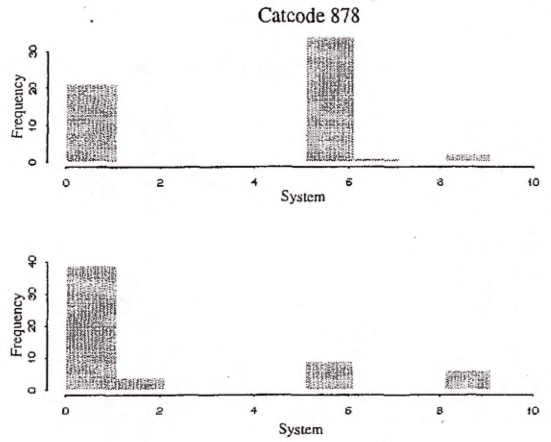

Figure 17. Allocation differences for a second target class.

Figure 18 provides information related to the timing aspects of the strategic timing problem. For reasons of survivability and delivery delays, we expect the allocation algorithms to preferentially select IC systems to attack time urgent targets and air delivered assets to be used against targets that are not time critical. From the figure we see that for a prompt response scenario, these allocation patterns are evident.

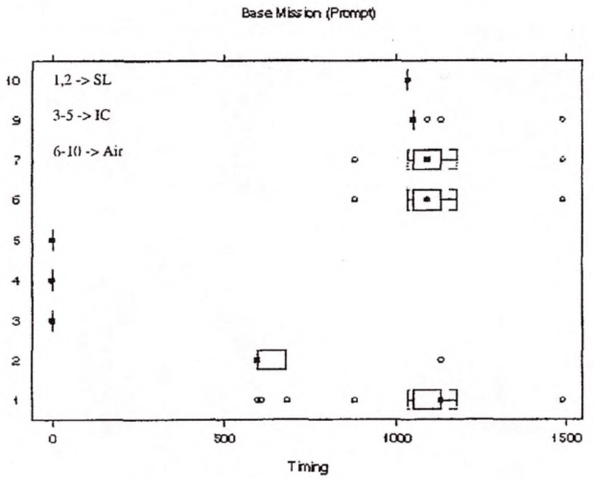

Figure 18. Timing allocation information for base prompt mission.

Other aspects of the targeting validation considerations were demonstrated in the fuzzy logic section presented earlier (Figures 4-7). We found that the generic characteristics of the targeting allocation algorithms demonstrated trends that were expected for the missions assessed.

Allocation Sensitivity Assessment. A sensitivity set of calculations were performed to assess the significance of model and system parameters in the allocation process. The exercise considered operational scenarios, mission suitability, system reliabilities, code convergence parameters, defuzzification methods, and the category code transformation matrix. The sensitivities were based on the L_{18} orthogonal matrix in which the 8 columns were fully assigned to analysis parameters. The table of experiments and settings are listed in the table of appendix B. A detailed description of the Taguchi analysis methodology follows in later sections.

The result of these 18 calculations are shown in the next figure.

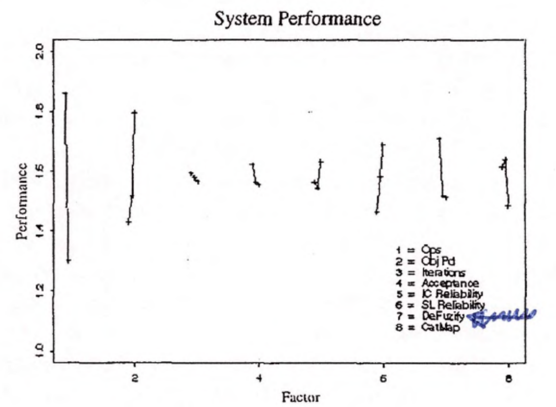

Figure 19. Mission fitness sensitivity.

The metric displayed in the Figure 19 is the fitness function defined by Equation 4. The expression provides numerical foundations for making comparisons for the different allocations of weapons to targets. The next figure demonstrates the sensitivity of mission Pd to the same set of parameters.

The vertical extent of a parameter in these plots indicates sensitivity to a design or analysis parameter. We also need to remember that each data bar represents the effect of that parameter averaged over all the remaining parameters. What we observe in these displays is a dominant system performance sensitivity to the operational scenario. The probability of damage (Pd) sensitivity plots really do not add a great deal of extra information but simply reinforce the sensitivity observations from Figure 20.

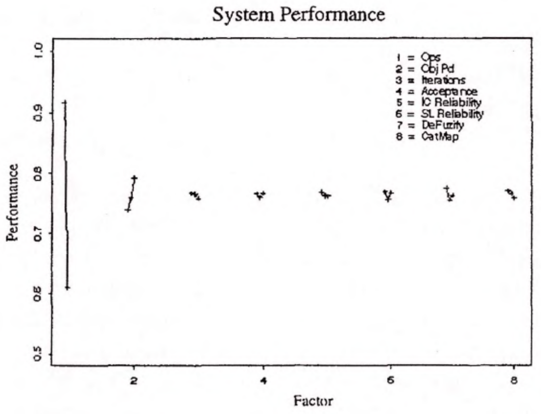

Figure 20. Mission Pd sensitivity results.

The fitness sensitivity plots indicate, that along with operational scenario, objective Pd or mission suitability is significant. The plot also indicates that submarine launched (SL) reliability and the de-fuzzification method needs to be examined closely when performing allocation studies. The implication of these results are a sensitivity of the design to perceptions of mission success and operational scenario.

Analysis recommendations include the use of the "centroid" de-fuzzification and a high user defined convergence acceptance level. The acceptance level acts as a threshold for improvement considerations in the allocation process.

Evolutionary Strategies (Weapon System Opt.).

The system optimization methodology is based on evolutionary strategies (ES). Basically, ES is a genetic algorithm which operates in a real solution space as opposed to a binary representation of the solution space employed in genetic algorithm optimizations. The problem is to solve equation 5 which is a representation of a vector function in x. The response surface defined by f may be of any order or complexity. The objective of the ES search algorithms is to identify an optimal solution to equation 4. It must be recognized that for any complex surface, the probability of finding the optimum is less than 1.0. What has been shown is that optimization techniques founded in the biological sciences do a better job of finding the optimal solution than classic linear programming methodologies.

$$y = f(\bar{x}) \qquad \text{Eqn. 5}$$

The "ES-chromosome" represents the vector solution to the equation and is represented in equation 6. The two vector components of the solution c_i are the nominal value associated with the solution vector and a search strategy parameter. Evolutionary strategies possess a characteristic that permits searches to be conducted in preferential directions of an n-dimensional space. These directions evolve during the course of the optimization iterations.

$$c_i = (\overline{op}, \overline{sp}) \qquad \text{Eqn. 6}$$

The following equations define the operators which are characteristic of an evolutionary strategies optimization methodology. Parametric or nominal value mutation is defined as:

$$\overline{op}_{mut} = \overline{op} + N_0(\overline{sp}) \qquad \text{Eqn. 7}$$

In this expression N_o represents a normal distribution about $\overline{\mathbf{op}}$ with a standard deviation of $\overline{\mathbf{sp}}$. The mutation process involves updating the nominal solution with random draws from the normal distribution defined by N_o.

Strategy mutation is defined by:

$$\overline{sp}_{mut} = \bar{s} \bullet \bar{A} \qquad \text{Eqn. 8}$$

$$A_i = \begin{cases} \alpha & E < 0.5 \\ 1/\alpha & E \geq 0.5 \end{cases} \qquad \text{Eqn. 9}$$

E is a random number: $E \in (0, 1)$. $\bar{s}$ is the vector of standard deviations used with N_o, and α has been recommended to be set to 1.3.

The equations delineated represent the optimization algorithm that was implemented for the weapon system optimization section of the analysis algorithms.

Weapon System Capability Optimization. The objectives of the weapon system optimization analysis is the identification of weapon system characteristics that best represent the solution to system needs which compliment the deployed stockpile. The algorithms also possess a capability to explore the broader question of stockpile composition based on delivery system characteristics, treaties and future mission scenarios. The algorithm, based on evolutionary strategies, has the ability to identify yields, inventories and option performance requirements to satisfy a mission.

Mission Analysis Results.

The analysis was executed on subsets of the scenarios and projections defined for this upgrade design effort. The basic subsets of missions consisted of START II scenarios, START III scenarios and sets of strategic reserve force (SRF) missions. The objectives were to identify potential mission sets for a strategic force in the near future as well as develop scenarios for system utilizations beyond a ten year time frame. Most projections of mission requirements do not explore conditions beyond this short time horizon. The scenarios that were developed were biased toward START III type projections. These scenarios defined inventories and targets that possessed characteristics similar to START II projections but at levels consistent with trends emerging in strategic treaties. The SRF missions did the best job of developing scenarios and provided some of the more stressing system requirements.

The first set of calculations performed for each of the three strategic environments consisted of sets of sensitivity calculations designed to identify the stressing conditions for mission performance of a replacement SL weapon system. The metric chosen to represent system suitability is defined in equation 9. The metric is defined as the standard deviation of the weapon radii assigned to the Mk4 divided by the standard deviation of the mission probability of damage.

$$S = \frac{\sigma_{Wr}}{\sigma_{Pd}} \qquad \textit{Eqn. 10}$$

This equation can be interpreted as characterizing a system which is robust, in terms of target coverage, and flexible, in terms of an ability to achieve a Pd close to the mission success parameter. The greater the value of S the better the system solution. The search for stressing conditions are parameter settings that drive the metric S to minimal values.

The first part of the effort is to identify combinations of parameters in each of the three subsets of mission which minimize the metric S. These parameters and options become the basis for defining system requirements of the modified system through confirmatory sets of calculations.

Sensitivity Space.

The independent variables identified consisted of

- Operational scenario (Prompt / Delayed).
  A prompt scenario reflects "launch on warning" scenarios, while the delayed operational scenario reflects the situation in which we succumb to a first strike before launching a retaliatory strike.
- Inventory.
  Inventory consists of the mix and numbers of ICBMs, SLBMs and air delivered assets in the deployed stockpile.
- Strategic reserve force size.
- Mission.
  Mission defines the target sets, the inventories, the policy, and the operational scenario.
- Objective probability of damage (Pd)
  This parameter is a reflection of the targeteers criteria for defining mission success.
- IC reliability.
- SL reliability.
- Number of replacement SL weapon system options.

Current / START II (Series A). The series A mission captures variations in the START II projections database. The target inventories are the largest in these projections and the weapon system inventories exhibit the broadest spectrum of capabilities. As a result we expect these scenarios to be the least stressing of the three subsets of strategic missions. The sensitivity calculations are structured to provide information indicating the most stressing set of conditions for this mission series. The results of these calculations provide the conditions which will be used in the confirmatory calculations which follow in later sections.

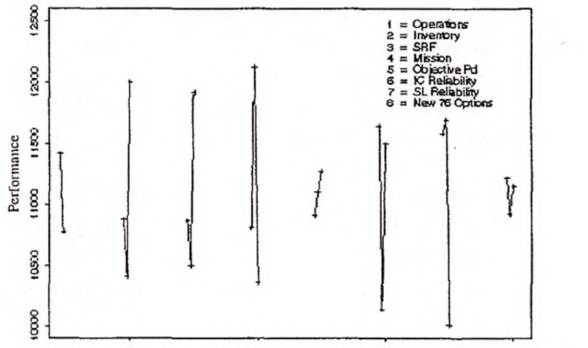

Figure 21. Sensitivity for experiment series A.

The performance metric employed in the assessment is the metric defined by equation 9. Figure 20 is the results of the series A set of analytical experiments. In these figures the vertical extent of each factor represents the sensitivity of that factor on the average of over all the other factors. The conditions which stress the system include: delayed response, inventory 2, mission C(definitions of inventories and missions are discussed in the classified addendum), a 2 boat SRF, "objective probability of damage" of 0.6, IC reliabilities of 0.85 and SL reliabilites of 0.9. The last three parameters including the number of new options are somewhat counter intuitive but may be attributed to confounding effects of other parameters in the analysis. This is also indicated by the change in slope of the parameters. The response surface indicates a degree of non-linearity in the performance metric. Each factor in the analysis was monotonically changed and if the dependence of the performance metric were linear we would expect monotonic changes in the metric. Of significance is the fact that all of the parameters exhibit consistently large sensitivities.

START III Environments (Series B). The series B mission set consisted of scenarios and projections that explore conditions associated with START III environments. The retirement of weapon systems and reduction of inventories would tend to drive the requirements for a replacement SL weapon system up. The series B sensitivity analysis utilized an L_{32} orthogonal matrix which allowed for 10 parameters to be studied.

The results of these experiments, Figure 21, indicate that there exists factors which dominate the problem. Mission and objective Pd are the dominant stressing conditions while the number of options provides a significant capability for countering these effects. As with the series A analysis the stressing conditions were identified based on this set of calculations and used in the confirmatory calculations.

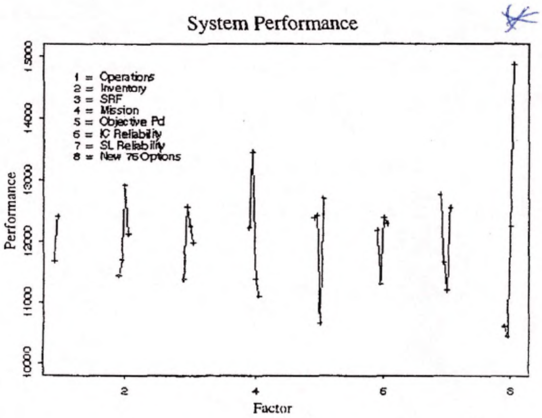

Figure 22. Sensitivity for experiment series B.

SRF Force Sensitivity. The SRF sensitivity analysis explored a subset of factors explored in the series A and B sets of conditions. The analysis was limited to four scenarios and situations in which the surviving SRF consisted solely of Mk4/W76 systems. This scenario was selected based on delivery system survivability considerations and on considerations for identifying the most robust set of system design requirements. Assuming a solely Mk4/W76 SRF force approximates a more stressing design environment. The four SRF missions consisted of two former Soviet Union satellite states, a North Korean mission and a Chinese mission. The sensitivity was limited to mission, objective Pd and the number of new options. This set of analytical experiments was based on a modified L_8 orthogonal matrix. The modification consisted of combining the first two factors in order to create a four level factor to capture the mission variability.

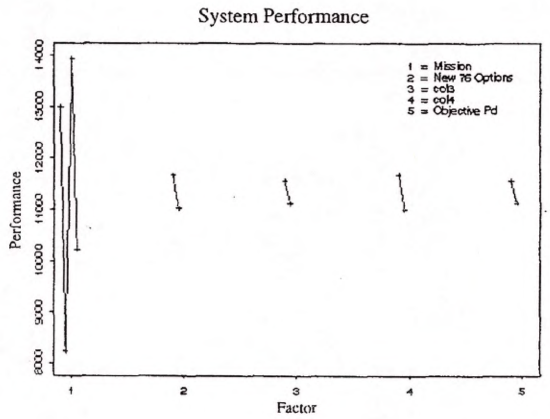

Figure 23. Sensitivity results for the SRF series of experiments.

The results, Figure 22, indicate that performance of the system is almost solely dependent on the SRF mission.

Confirmatory Analyses and Results.

The final phase of a Taguchi analysis is the confirmatory calculations which bases factor settings on the results of the sensitivity studies. The object of the analysis is to define the system level requirements of a replacement SL weapon system within the context of a strategic force. The sensitivity studies were structured to identify conditions which would lead to the most constrained set of system requirements for the three mission subsets. Again these mission sub-sets consisted of near term projections, moderate range scenarios / projections, and the SRF mission subset.

Current / START II (Series A). The conditions of the confirmatory analysis were delineated in the series A sensitivity section of this note. What follows is a series of plots providing detailed allocation information, stockpile allocation information, convergence data, and the distributions associated with the effective CEP requirements developed for the system. The decision metric is defined by equation 9.

Figures 23 and 24 are representations of the raw data captured in equation 9. The first figure shows the coverage of each weapon system in the inventory in terms of target weapon radius. Information contained in these plots includes the mean, the dot inside the boxes. The inter-quartile range is defined by the box, while the whiskers define the limits of the standard span, i.e. 1.5* inter-quartile range. Points delineated beyond the whiskers are the outliers. These figures provide regimes of weapon system responsibility given specific system characteristics. The indices on the vertical axis correlate to the weapon system within the strategic inventory. Systems 1 and 2 are the SLs, 3,4 and 5 would represent the ICs and the remaining the air delivered assets. Systems 3 and 4 are unallocated in the cases depicted in the figures.

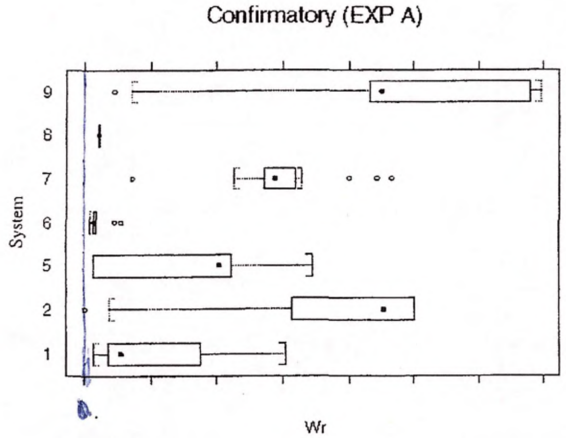

Figure 24. Weapon radius range of targets assigned to weapon systems.

Figure 23 delineates the assigned area of responsibility, the next figure characterizes the capability of the system on the assigned area of responsibility. A infinitely capable system would result in a simple vertical line at a level equivalent to the objective Pd value. As we can see from the figure none of the systems (those with statistically significant allocations) exhibit this characteristic.

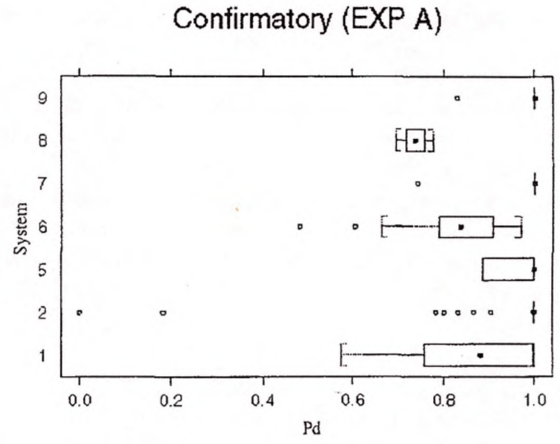

Figure 25. Performance range of system against targets allocated.

Figure 25 captures the allocation statistics for all systems within the strategic inventory, including the newly optimized Mk4/W76 system. From the figure we see that for the series A mission subset 65-70 percent of the mission is being covered by the SL branch of the triad.

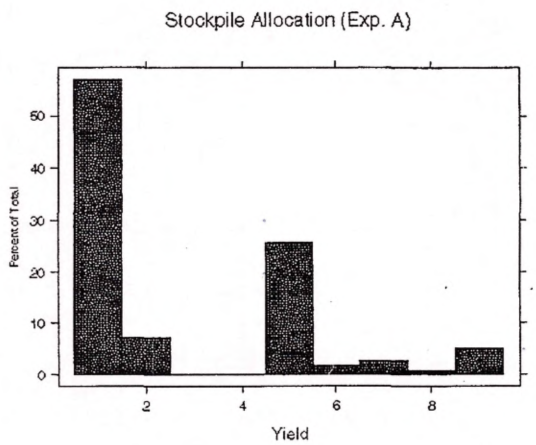

Figure 26. Deployed stockpile allocation for mission scenario A.

The mission series A is a weapon rich scenario. Given the optimized capabilities of the replacement SL weapon system, this system is an extremely import component in a strategic weapons mix. The effective CEPs for the system are defined in the lower left panel of Figure 26. Five options evolved which had targets assigned to them.

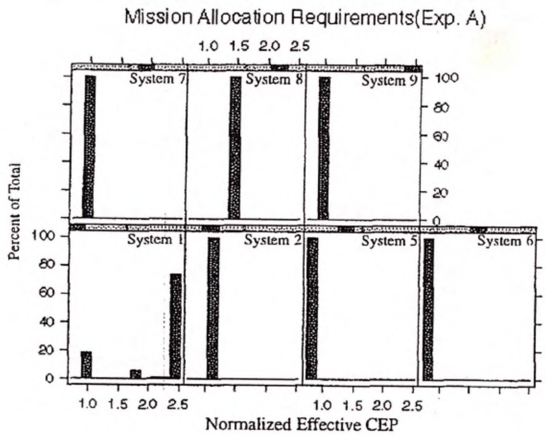

Figure 27. Required effective CEPs and associated distributions.

Based on the two previous figures we see that nearly 50% of the mission could be successfully attacked by a Mk4 system capability of 2.5. Similarly, less than 14% would require a Mk4 system with a 1.0 normalized capability.

A concern when using biologically inspired optimization algorithms is the probability of convergence to a maximum in the response space. Figure 27 shows that we indeed found an optimum early in the calculational series. We can also see that for this series in the mission subsets, we approached a relatively high mission fitness, greater than 1.9 of a theoretical maximum of 3.0.

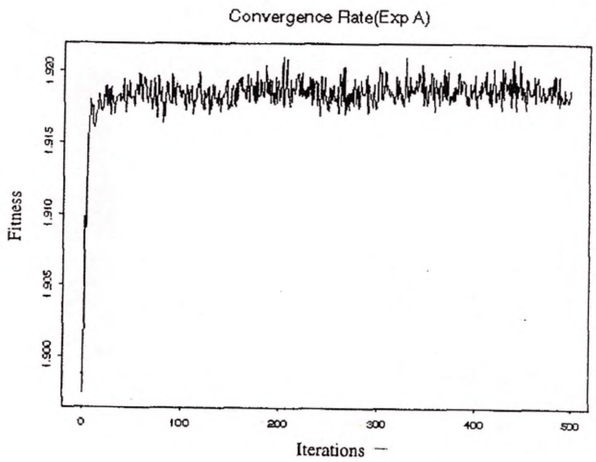

Figure 28. Convergence information for experiment series A.

START III Environments (Series B). The series B mission subset is a target rich scenario. In this case some targets will survive uncovered by a one-to-one targeting philosophy. The figures which follow provide identical information to the information generated for the series A mission subset. The first point to notice with these calculations are the diminished responsibility assigned to the replacement SL weapon system. This is potentially due to a number of factors including the uncovering of soft targets because of priority considerations in a target rich environment, and a different weapons mix resulting from treaty considerations. A significant number of second order factors come into play some of which are captured in the allocation and optimization algorithms.

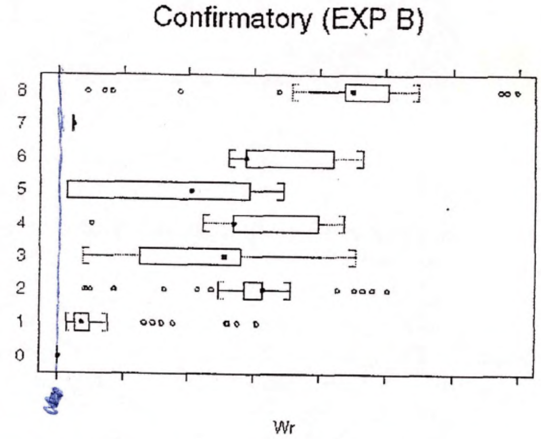

Figure 29. Weapon radius range of targets assigned to weapon systems.

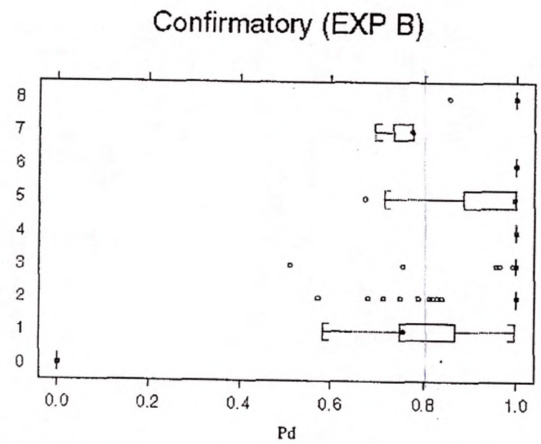

Figure 30. Performance range of system against targets allocated.

The figures which capture the essence of the roles and requirements are shown in Figures 30 and 31. We see that

Iterations

given the strategic inventories associated with this mission subset, we still see over half the mission being covered by the SL branch of the triad. There is however a diminished role of the Mk4/W76 in the allocations, less than 40%.

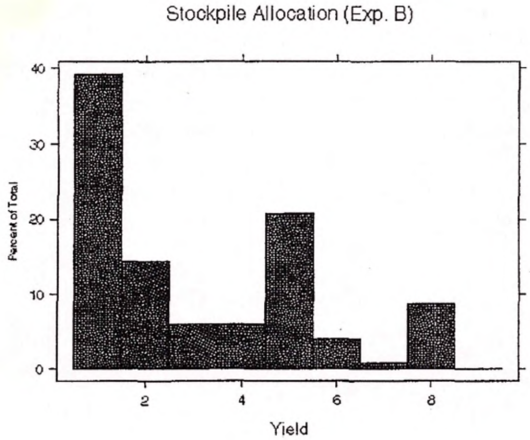

Figure 31. Deployed stockpile allocation for mission scenario B.

As in the case of the series A mission subset, the recommended set of effective CEPs range from 1.0 to 2.5 normalized feet, the limits explored by the optimization algorithms. We find in this case however that only 25% of the mission requires the largest effective CEP and approximately only 8% requires the tightest effective CEP.

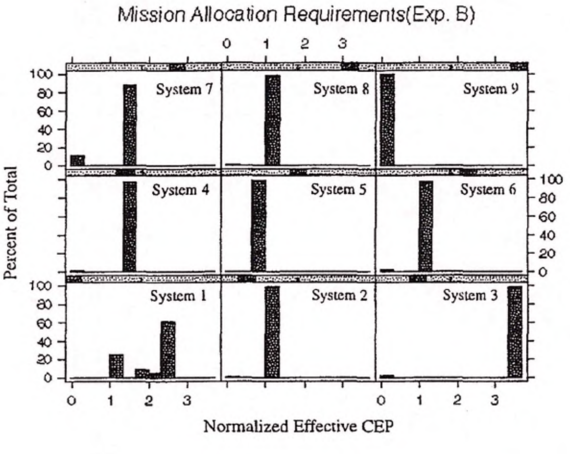

Figure 32. Required effective CEPs and associated distributions.

As with series A, the convergence to a solution occurred early in the calculational series. The solution converged to a level lower than that of the first series in large part to the uncovered targets which are considered to contribute a value of zero(a penalty) to the fitness functions.

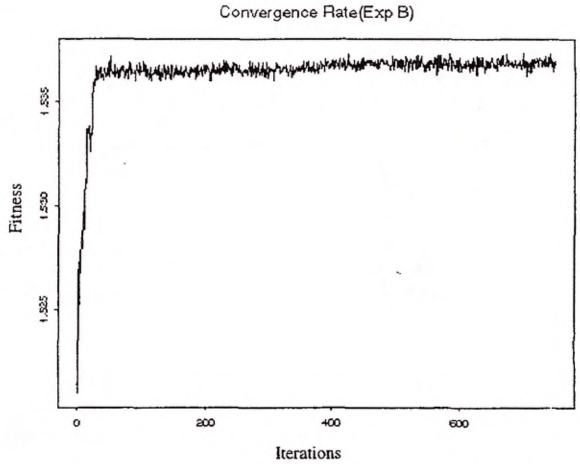

Figure 33. Convergence information for experiment series B.

SRF Force Confirmatory. The SRF mission subset consisted of 4 missions generated from target databases on regional missions. SRF missions are assumed to exist under conditions of limited weapon system inventories, in this case only M4/W76 weapon systems, and limited target sets. The sensitivity analysis conducted was used to identify the most stressing environment for the Mk4 system, the conditions identified were used in the SRF confirmatory calculations. The results of these calculations are defined in the next plot.

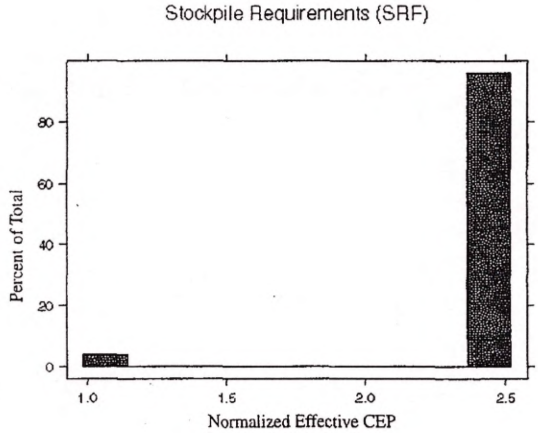

Figure 34. SRF effective CEP requirements and associated distribution.

We find under these conditions that a system exhibiting maximum capabilities will be employed 95% of the time while the lowest capability would be used only 5% of the time. The implications are that the SRF mission, based on the 4 case subset, will not be a system requirements driver in this design effort.

Exploratory Analysis.

The tool possesses the capability to optimize on yields, inventories as well as accuracy constraints. With this capability we also have the ability to explore the optimal configuration of the strategic stockpiles. An exploratory set of calculations were performed to find the optimal stockpile given a mission with a distribution of targets comparable to a current mission, "Scenario A" of our mission set. The sensitivity study explored the effects of objective Pd, SRF force size, reliabilities of the delivery systems, as well as the effects of the number of potential yields and number of options(effective CEPs) of the new systems. The results of those analyses are provided in figure 34.

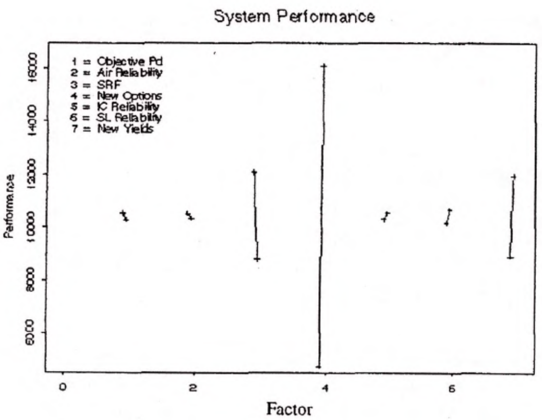

Figure 35. Stockpile optimization sensitivity assessment.

The number of options per system is the most important design parameter with yields and SRF force size being the next most important design and operational parameters. The confirmatory calculation produced the following results.

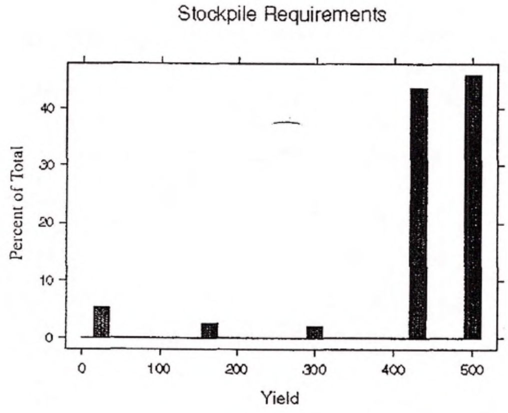

Figure 36. Yield distribution for an optimized stockpile.

The yield distribution requirements are presented in Figure 35. The optimal stockpile would contain five basic systems with yields ranging from 25 to 500 Kt. The corresponding option requirements are provided in Figure 36. The systems are numbered from lower left to upper right, 1-6. The two 25 kt systems correspond to 2 and 6 in the figure. Of the remaining systems, system 1 is a 431 kt system, system 3 is 167 kt, system 4 is at 500 kt and system 5 is at 302kt.

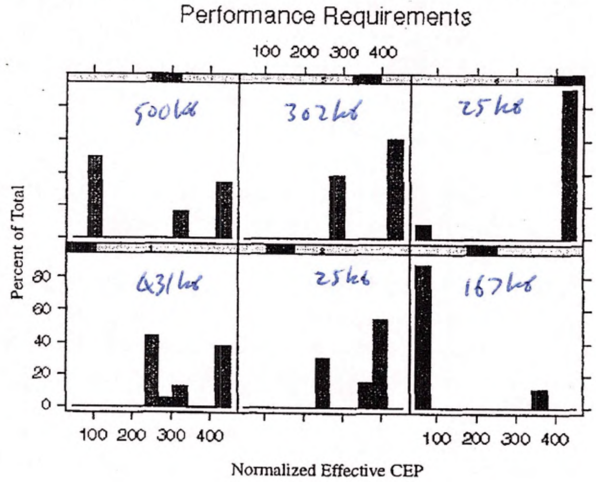

Figure 37. Effective CEP requirements for each system in the optimized inventory.

Decision Issues.

The following table summerizes the system level requirements and the percent of target coverage associated with the option for the three mission subsets. The percentages in the headers is the percent of targets assigned to the Mk4 weapon system.

Table 4: Confirmatory analysis results.

Series A 58%		Series B 39%		SRF 100%	
1.0	11%	1.0	6%	1.0	4%
1.8	4%	1.03	3%	2.5	96%
2.13	2%	1.79	4%		
2.23	1%	2.18	2%		
2.5	40%	2.5	24%		

At the smallest normalized effective CEPs, series A and B, the option is used on approximately 10% of the targets, while for the largest effective CEP, the system is used on 24 to 40% of the series A or B targets.

Follow-on Activities

The results delineated in earlier sections provide information for use in the system development effort. The remainder of the section provides the context in which the data is used. One of the responsibilities of the systems engineer is to provide transformations between system level requirements and the sub-system level metrics used to assess the performance of the sub-system. In the case of this effort the sub-system design engineers are using Monte-Carlo techniques to determine the probability of kill (P_k) of a concept against a target set. The transformation between effective CEP requirements and concept Pk is defined by equation 2.

A re-statement of the development activity and the information generated follows: **Scenario development** provides mission details including weapon system inventories, target distributions, range distributions, and mixes of delivery platforms. **Range distributions** provide weightings of pre-reentry covariances. **Target distributions and locations** provide target clustering distributions which enable the analyst to assess foot printing capabilities as functions of warhead weight and yield. **Weapon system optimization** provides information delineating the subset of mission targets allocated to the new / modified weapon system concept. This effort also generates the effective CEP requirements for the system and fuzing options.

Recommendations for further Development.

The next couple of points capture considerations for further work or efforts that should be considered in future development efforts. The two basic issues concern the mission developments, and the technology for completing the requirements development process in a manner that is 1) technically feasible, and 2) more attuned to classic systems engineering development approaches.

Trend Analysis of Missions.

The scenario development considered a static target database for use in defining future missions. This approach is a reasonable first order approach to mission analysis. The problem with this approach is it lacks consideration of trends in asset protection. We have seen from historical evidence that targets are not static but under go design modifications that in some cases result in diminished vulnerabilities, and / or greater location uncertainties. Targets are deployed in deeper bunkers, the bunkers are better engineered, or take better advantage of the natural terrain and geology. Taking these types of dynamics into consideration might have resulted in modified target distributions from which the missions were developed.

Targeting Rule Base Issues.

Some effort should be expended to explore the use of genetic programming techniques to find the rule set which most closely approximates the current targeting philosophy of strategic targeteers. The rule set used in this study is based on a best guess, based on generic targeting considerations. The fuzzy approach was employed to provide a degree of flexibility for the exploration of policy issues associated with strategic targeting. In order to explore these excursions, a rule set needs to be identified that exhibits a high degree of fidelity with current policy.

There are two basic methodologies useful for developing target allocation rules. The first is to follow an evolutionary approach similar to the process that resulted in the current targeting heuristics. It is suggested that this evolutionary approach be pursued in order to make the process of capturing complex non-linear dependencies tractable. The second more sophisticated approach is to write a wrapper for the allocation algorithms in which a genetic algorithm (GA) employing cyclic permutations searches for combinations of fuzzy operators and terminals to identify an optimal target rule set. This approach requires a known solution to act as the fundamental training set.

C4ISR Projections

A replacement SL weapon system will remain in the deployed stockpile for 30 plus years. Command and control development efforts are likely to result in capabilities that could permit re-targeting of a strategic weapon system in real time. This requires that target recognition assets have evolved capabilities sufficient to assess the status of a silo or the location of re-locatable assets and could securely communicate this information to the missile / bus system. With stockpile size trends resulting from treaties, the value of the assets continues to increase.

The technology which may make real time targeting possible revolves around the concept of cyber-agents. The possibility exists for the agents to orchestrate the identification, location and projected location of strategic targets at times consistent with the speed of a SRT and the time from release to impact and provide that information to targeting agents which could correct preset conditions within the constraints of the bus energy. What might the implications to system performance be under these conditions. We no longer would have to shoot at potentially hard empty holes, but could engage targets with a high degree of location uncertainty.

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DE-AC04-94AL85000.

APPENDIX A **Transformation between category codes and descriptive parameters.**

Table 5: Category code and variable transformation with basic rule set. (Descriptions can be found in the classified addendum)

CatCode	Description	Counter_lethality	Mission	Function	HOB	Timing	Weight
21100	Petrol plant	20	50	85	0	1774.77	0.496094
21300	~~Iron+Steel plant~~	10	50	85	0	1785.28	0.496094
21500	Pipeline support	10	50	85	0	1785.28	0.496094
41100	Radio/Satellite stati	85	10	45	162.906	64.9121	0.59863
41400	Comms Centre	80	10	45	164.151	123.194	0.59863
42100	Electricity plant	10	50	90	0	1785.3	0.496094
42200	Hydroelectric plant	10	50	90	0	1785.3	0.496094
42600		10	50	90	0	1785.3	0.496094
42700		10	50	90	0	1785.3	0.496094
45100	Bridge	20	50	90	0	1776.07	0.496094
45300	Railway yard	20	50	90	0	1776.07	0.496094
45500	Railway crossing dam	10	40	85	0	1687.43	0.566804
45900	Rail facilite	30	40	35	1979.33	1388.18	0.339355
60300	NW fabrication	80	5	135	0.0310793	350.962	0.851451
60400	NW Storage	85	5	130	0.0260747	358.633	0.850451
60500		80	5	35	1926.85	349.161	0.543991
61100	Aircraft factory	20	15	10	2056.13	1748.24	0.344194
63200	Weapons factory	15	15	15	1995	1746.39	0.403487
63400	Artillery "	10	15	15	1995	1747.89	0.403487
63500	Rocket/Grenade launcher "	10	15	15	1995	1747.89	0.403487
64400	Combat vehicle factory	10	15	15	1995	1747.89	0.403487
66100	CW factory	75	30	135	0	365.458	0.818808
66200	CW Store	75	35	130	0	364.996	0.807953
66500		75	30	135	0	365.458	0.818808
66600		75	35	130	0	364.996	0.807953
67200	Shipyard	90	15	30	2034.09	359.038	0.451828
68000	Missile factory	30	50	10	2056.13	1684.75	0.354194
68100	ICBM factory	20	45	10	2056.13	1774.25	0.333109
68200	Tactical missile -"- —	20	45	10	2056.13	1774.25	0.333109
68300	Naval -"- —	15	45	10	2056.13	1774.25	0.333109
68400	ABM -"- —	20	45	10	2056.13	1774.25	0.333109
68500	SAM -"- —	15	50	15	1995	1783.65	0.39039
68600	AAM -"- —	20	50	15	1995	1774.77	0.39039
68700	Spacesys factory	15	50	15	1995	1783.65	0.39039
74100	National Govt Control	90	50	50	142.745	44.7661	0.580098
76000		90	50	50	142.745	44.7661	0.580098
80000	Airfield	95	15	110	0.059728	126.551	0.881386
80050	~~Heliport~~	90	30	110	0	359.217	0.818808
80100		70	40	65	0	363.039	0.566804
81100	Aviation HQ national	90	10	55	160.759	44.7661	0.602328
81200		85	10	55	160.759	64.9121	0.593928

Table 5: Category code and variable transformation with basic rule set. (Descriptions can be found in the classified addendum)

CatCode	Description	Counter_lethality	Mission	Function	HOB	Timing	Weight
81300	~~Naval aviation HQ~~	80	25	55	164.699	356.11	0.588974
81400	Naval aviation HQ	60	25	55	164.699	360.824	0.588974
82200	Air Defense CP	85	70	110	0	64.9121	0.851482
82400	~~Space facilities~~	85	70	110	0	64.9121	0.851482
82600		85	70	110	0	64.9121	0.851482
83200		85	5	50	142.745	64.9121	0.584779
84100	Space facilities	85	10	55	160.759	64.9121	0.593928
84500	Military -"-	90	70	45	168.072	44.7661	0.624703
85100	Radar	90	70	110	0	44.7661	0.851482
85300	Missile control Radar	95	70	110	0	41.6943	0.851482
86100	Air Depot	70	45	90	0	1661.97	0.516997
86200	Air Ammo Depot	70	55	90	0	1661.97	0.516997
86900		70	55	90	0	1661.97	0.516997
87100	ICBM	95	5	110	0.022495	41.6943	0.88307
87200	Missile complexes	90	70	110	0	44.7661	0.851482
87400	Missile HQ	90	5	50	142.654	44.7661	0.584779
87600	Missile support	80	10	35	1926.85	349.576	0.522452
87800	Missile launch control	95	5	50	142.407	41.6943	0.585192
87900	Naval missile harbor	70	45	80	0	331.556	0.516997
88100	Rail mobile missile	95	5	110	0.022495	41.6943	0.88307
89100	National Command fac.	95	50	50	142.745	44.4562	0.584356
89200		90	50	50	142.745	44.7661	0.580098
89500	Joint CP	85	50	50	142.745	64.9121	0.566483
89700		80	50	55	164.699	127.29	0.548832
91000	Ground force HQ	55	30	55	164.699	365.186	0.627476
92000	Ground force depot	50	55	90	0	1457.79	0.496992
95100	Surface ship base	50	50	75	0	387.007	0.496094
95200	Submarine base	90	20	110	0.204469	293.47	0.858072
96100	Naval HQ Nat'n	50	30	55	164.699	365.186	0.627476
96200	Naval HQ Flotilla	40	30	55	164.699	867.286	0.627476
96300		30	30	55	164.699	1254.39	0.627476
97200	Naval ammo stor.	40	30	85	0	1330.21	0.818808

0 = Strat offense
30 = Tac offense
50 = Multi-mission
70 = Strat defense
100 = Tac def

10 = Fabricate
30 = Support
50 = C3
70 = Combat
90 = ~~[illegible]~~ Str storage
100 = Attack
130 = WMD storage.

APPENDIX B **Experimental configurations for validation calculations.**

The prompt operational scenario reflects a launch on warning philosophy, while the delayed response reflects a philosophy of suffering a first strike and then retaliating with the remaining

Table 6: Sensitivity analysis setups.

Exp. No.	Plan	Objec Pd	Iter.	Accept	IC Relia.	SL Relia.	Defuzz	Cat Code
1	Prompt	0.6	100	1.0	0.7	0.8	centroid	brad
2	Prompt	0.6	175	1.5	0.85	0.9	ave max	mike
3	Prompt	0.6	250	2.0	1.0	1.0	max	brad
4	Prompt	0.75	100	1.0	0.85	0.9	max	brad
5	Prompt	0.75	175	1.5	1.0	1.0	centroid	brad
6	Prompt	0.75	250	2.0	0.7	0.8	ave max	mike
7	Prompt	0.9	100	1.5	0.7	1.0	ave max	brad
8	Prompt	0.9	175	2.0	0.85	0.8	max	brad
9	Prompt	0.9	250	1.0	1.0	0.9	centroid	mike
10	Delay	0.6	100	2.0	1.0	0.9	ave max	brad
11	Delay	0.6	175	1.0	0.7	1.0	max	mike
12	Delay	0.6	250	1.5	0.85	0.8	centroid	brad
13	Delay	0.75	100	1.5	1.0	0.8	max	mike
14	Delay	0.75	175	2.0	0.7	0.9	centroid	brad
15	Delay	0.75	250	1.0	0.85	1.0	ave max	brad
16	Delay	0.9	100	2.0	0.85	1.0	centroid	mike
17	Delay	0.9	175	1.0	1.0	0.8	ave max	brad
18	Delay	0.9	250	1.5	0.7	0.9	max	brad

APPENDIX C **Inventories Used in current, START II, and START III scenarios.**

See Classified Addendum for table of weapon system inventories. "Information Adendum To Weapon System Requirements Analysis", to be published.

APPENDIX D **Experiment A, current and START II environments.**

Table 7: Taguchi setup for Current and Start II scenarios, L_{18} matrix.

Exp No.	Ops	Inventory	SRF (Boats)	Mission	Obj Pd	Reliability IC	Reliability SL	No. New Options
1	Prompt	1	1	A	0.6	0.7	0.8	2
2	Prompt	1	2	B	0.75	0.85	0.9	4
3	Prompt	1	3	C	0.9	1.0	1.0	6
4	Prompt	2	1	A	0.75	0.85	1.0	6
5	Prompt	2	2	B	0.9	1.0	0.8	2
6	Prompt	2	3	C	0.6	0.7	0.9	4
7	Prompt	3	1	B	0.6	1.0	0.9	6
8	Prompt	3	2	C	0.75	0.7	1.0	2
9	Prompt	3	3	A	0.9	0.85	0.8	4
10	Delayed	1	1	C	0.9	0.85	0.9	2
11	Delayed	1	2	A	0.6	1.0	1.0	4
12	Delayed	1	3	B	0.75	0.7	0.8	6
13	Delayed	2	1	B	0.9	0.7	1.0	4
14	Delayed	2	2	C	0.6	0.85	0.8	6
15	Delayed	2	3	A	0.75	1.0	0.9	2
16	Delayed	3	1	C	0.75	1.0	0.8	4
17	Delayed	3	2	A	0.9	0.7	0.9	6
18	Delayed	3	3	B	0.6	0.85	1.0	2

APPENDIX E **Experiment B, START III environments.**

Table 8: Taguchi setup for START III scenarios, L'$_{32}$ matrix.

Exp No.	1 Ops	2 Inven-tory	3 SRF (boats)	4 Mission	5 Obj Pd	6 Reliability IC	7 Reliability SL	8 No. New Options	9 Acc. of IC (Un-Modeled)
1	Prompt	11	0	D	0.6	0.7	0.7	2	0.7
2	Prompt	11	1	E	0.7	0.8	0.8	4	0.8
3	Prompt	11	0	F	0.8	0.9	0.9	6	0.9
4	Prompt	11	1	G	0.9	1.0	1.0	8	1.0
5	Prompt	12	0	D	0.7	0.8	0.9	6	1.0
6	Prompt	12	1	E	0.6	0.7	1.0	8	0.9
7	Prompt	12	0	F	0.9	1.0	0.7	2	0.8
8	Prompt	12	1	G	0.8	0.9	0.8	4	0.7
9	Prompt	13	0	E	0.8	1.0	0.7	4	0.9
10	Prompt	13	1	D	0.9	0.9	0.8	2	1.0
11	Prompt	13	0	G	0.6	0.8	0.9	8	0.7
12	Prompt	13	1	F	0.7	0.7	1.0	6	0.8
13	Prompt	14	0	E	0.9	0.9	0.9	8	0.8
14	Prompt	14	1	D	0.8	1.0	1.0	6	0.7
15	Prompt	14	0	G	0.7	0.7	0.7	4	1.0
16	Prompt	14	1	F	0.6	0.8	0.8	2	0.9
17	Delayed	11	0	G	0.6	1.0	0.8	6	0.8
18	Delayed	11	1	F	0.7	0.9	0.7	8	0.7
19	Delayed	11	0	E	0.8	0.8	1.0	2	1.0
20	Delayed	11	1	D	0.9	0.7	0.9	4	0.9
21	Delayed	12	0	G	0.7	0.9	1.0	2	0.9
22	Delayed	12	1	F	0.6	1.0	0.9	4	1.0
23	Delayed	12	0	E	0.9	0.7	0.8	6	0.7
24	Delayed	12	1	D	0.8	0.8	0.7	8	0.8
25	Delayed	13	0	F	0.8	0.7	0.8	8	1.0
26	Delayed	13	1	G	0.9	0.8	0.7	6	0.9
27	Delayed	13	0	D	0.6	0.9	1.0	4	0.8
28	Delayed	13	1	E	0.7	1.0	0.9	2	0.7
29	Delayed	14	0	F	0.9	0.8	1.0	4	0.7
30	Delayed	14	1	G	0.8	0.7	0.9	2	0.8
31	Delayed	14	0	D	0.7	1.0	0.8	8	0.9
32	Delayed	14	1	E	0.6	0.9	0.7	6	1.0

Inventory Scaling

- D - 0.345
- E - 0.388
- F - 0.364
- G - 0.364

APPENDIX F SRF experimental setup.

Table 9: Taguchi setup for optimized stockpile scenario, L_{16} matrix.

Exp No.	1 Obj Pd	2 Air Relia	3 SRF	4	5	6	7	8 No. CEPs	9	10 IC Relia	11	12 SL Relia	13	14	15 No. Yields
1	0.7	0.7	0					3		0.7		0.7			3
2	0.7	0.7	0					6		0.9		0.9			6
3	0.7	0.7	0					3		0.7		0.9			6
4	0.7	0.7	0					6		0.9		0.7			3
5	0.7	0.9	15%					3		0.9		0.7			6
6	0.7	0.9	15%					6		0.7		0.9			3
7	0.7	0.9	15%					3		0.9		0.9			3
8	0.7	0.9	15%					6		0.7		0.7			6
9	0.9	0.7	15%					3		0.7		0.7			6
10	0.9	0.7	15%					6		0.9		0.9			3
11	0.9	0.7	15%					3		0.7		0.9			3
12	0.9	0.7	15%					6		0.9		0.7			6
13	0.9	0.9	0					3		0.9		0.7			3
14	0.9	0.9	0					6		0.7		0.9			6
15	0.9	0.9	0					3		0.9		0.9			6
16	0.9	0.9	0					6		0.7		0.7			3

APPENDIX G **Sample input data set.**

Sk_Confirm	*Name of the file*
ScaledInv 0.357	*Scaling of inventories to match the ratio of targets to weapons*
Weapons 0 6	*Old and new weapons*
Options 0 6	*Old and new options*
SysRelia 0.9	*System reliability*
Response 120 10 2400	*Delivery system characteristic timing*
eoi	

Options 0 6 SysRelia 0.8 Response 45 -3 60 eoi
Options 0 6 SysRelia 0.7 Response 1200 75 3000 eoi

Options 0 6 SysRelia 0.9 Response 120 10 2400 eoi
Options 0 6 SysRelia 0.8 Response 45 -3 60 eoi
Options 0 6 SysRelia 0.7 Response 1200 75 3000 eoi

Population 25	*ES population size*
Convergence 400	*Convergence interations*
Mutation 0.125	*Mutation probability*
ObjectivePD 0.75	*Mission success paramter*
Conv_PPM 10000	*Convergence criteria in PPM*
Debug	*Generates extra output data*
Constraint 48	*Total number of parameters being optimized; (6 systems with 6 yields, 6 inventories, and 6 options. 6*(1+1+6)*
0.5	*Scale factor for evolutionary strategy search parameter*
25 500	*Range for yield search*
250 1275	*Range of inventory levels*
100 500	*Range of option capabilities*
100 500	...
100 500	
100 500	
100 500	
100 500	

25 500
0 425
200 500
200 500
200 500
200 500
200 500
200 500

25 500
100 850
50 500
50 500
50 500
50 500
50 500
50 500

25 500
250 1275
100 500
100 500
100 500
100 500
100 500
100 500

25 500
0 425
200 500
200 500
200 500
200 500
200 500
200 500

25 500
100 850
50 500
50 500
50 500
50 500
50 500
50 500

Scenarios 1	*Number of scenarios in the optimization*
6 1 2 3 4 5 6	*Number and which warheads are in each scenario*
Scenario.A	*File name of the target database used in optimization*
eoi	

APPENDIX H **Table of contents for code listings.**