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Systems Engineering Analysis of Kinetic Energy Weapon Concepts

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Abstract

This study examines, from a systems engineering design perspective, the potential of kinetic energy weapons being used in the role of a conventional strategic weapon. Within the Department of Energy (DOE) complex, strategic weapon experience falls predominently in the nuclear weapons arena. The techniques developed over the years may not be the most suitable methodologies for use in a new design/development arena. For this reason a more fundemental approach was pursued with the objective of developing an information base from which design decisions might be made concerning the conventional strategic weapon system concepts. The study examined (1) a number of generic missions (2) the effects of a number of damage mechanisms from a physics perspective (3) measures of effectiveness (MOE's), and (4) a design envelope for kinetic energy weapon concepts. With the base of information a cut at developing a set of high-level system requirements was made, and a number of concepts were assessed against these requirements.

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Systems Engineering Analysis of Kinetic Energy Weapon Concepts*

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Executive Summary

A study was conducted to examine the utility of using/developing conventional weapons in a strategic mode. Measures of effectiveness (MOE) were developed for use in concept trade-off studies and for potential use by the Department of Defense (DOD) to help them assess the viability of incorporating new systems concepts into their force structure. The conduct of the study was based on a systems engineering process model founded in the work of J.O. Grady (Grady, 1995). As part of the information generation activities a fundamental mission and physics damage effects analysis was conducted. This information was used to develop the MOEs for use in the assessment of weapon system concepts.

The systems engineering study included a high level functional analysis to identify systems which would either be required or could be used by a conventional strategic weapon system. the associated requirements analysis examined the relative importance of these subsystems and provided the foundations needed to develop first level requirements. The final element was a synthesis activity which examined a number of system concepts, and trade-off analyses were conducted to assess the merits of the concepts.

At the conclusion of the study no concept emerged as a viable conventional strategic weapon system concept; however, due to the depth of study and the broad range of possible missions, a solution was not precluded. Cursory examination of concepts for use in a chemical/biological kill arena proved to be ineffective due to insufficient energy being transferred to the agents to ensure destruction. There appears to be a reasonable likelihood of delivering a weapon system to targets, either armored or shallowly buried, with a high probability of success. The difficulty in these situations is identifying a mechanism with sufficient energy potential to demonstrably destroy the target.

The following areas should be pursued to provide a more complete assessment of conventional strategic concepts. Expanded studies need to: (1) examine damage mechanisms for optimum penetration velocities; (2) roll secondary weapons effects into the analysis; (3) perform a more detailed operational analyses; and (4) identify the energy content needed in an explosive material to provide acceptable levels of damage as a function of weapon system loads, and damage mechanisms.

* Additional time & computer support provided by Complex Engineering Analytics (CEA)

1.0 Introduction

The defense community has for many years had to devise tactics and design acquisition programs around superpower conflicts. The changes in the global politics make many of the classic military solutions unacceptable. The result is that the defense community must pay greater attention to the full range of the conflict spectrum, not just the extremes of confrontation. Philosophies and strategies that have been with us throughout the cold war are being reexamined in this new light. The implications of this reexamination are beginning to be seen in weapon system architectures and concepts. Requirements for rapid response, verifiable results, preservation of national sovereignty, and controlled collateral damage present the defense design community with a difficult set of conflicting design criteria.

The overriding constraint in any design decision is to preserve our assets. There is a tendency to lose sight of the fact that far too often it is American personnel who are put in harms way, and any design must minimize the loss of US forces. The philosophies of war are being corrupted by an outspoken element of society that does not comprehend or attempt to understand the lessons of history through the historical teachings of Sun Tzu, or Clausewitz.

The Navy community is beginning to examine alternative strategic theories of defense which are causing us to examine new, less lethal concepts for integration into the Navy force structure. The concepts involve precision strike weapons, kinetic energy warheads, shaped charge warheads, as well as the more traditional explosive warhead design. The solution concepts continue to rely on the age-old solution, "drop something that breaks things." What has not yet been included in these weapon system studies are nontraditional concepts of disruption and destruction. Clausewitz writes about "the fog of war," which would suggest information. The ability to disrupt a communications capability can be thought of in traditional terms of finding it and breaking it or in a nontraditional sense of overloading it. We have seen the impact on the phone system when too much activity is occurring; we might find ways of infiltrating a communications net and placing our own information on the system, decreasing available bandwidth and tying up assets that are trying to identify real from spurious messages. It would seem that counteracting a weapon system with a system utilizing similar effects might provide some leveraging possibilities. Use chemical agents against chemical weapons, or biologics against biological weapons, and information against intelligence systems. The more sophisticated the adversary's weapon systems are, the greater the potential for disruption and effectiveness mitigation. As researchers we should be identifying conditions/situations that might permit the introduction of new technologies into the defense force structure. Near-term conventional solutions are best left to the commercial arena.

Experience in past nuclear weapon design efforts provides a foundation from which modified design and analysis methodologies can evolve. The problems associated with a conventional strategic weapon design effort are potentially greater than those of a nuclear design. One reason is the mission and effectiveness analyses become more complex because of the need to include uncertainty and noise in the problem. Nuclear weapon designs permit the application of force to overwhelm variability and uncertainty, while in the conventional arena we need ingenuity. The analysis will therefore examine weapon system design effort from a broader perspective. It will identify MOEs and analytical approaches that can assess system concept performance. The analysis will also identify the "design space" leading to credible weapon systems and the union of this space with the constraints imposed by the delivery system. The final

Grady defines task E: "Work is accomplished to develop and maintain an understanding of the customer's needs. Efforts are made to develop concepts that solve anticipated customer needs and to communicate these to the customer." I would take this one step further to include providing the customer with tools he can use to assess the credibility of concepts presented for procurement.

There exist eight subtasks associated with the marketing and preconcept task. One, company funded feasibility studies, is the core of activities which I pursued in this study. Figure 2 provides a process view of these activities. Subtask E38, systems analysis and evaluation, is presented as an encompassing task. This was done to indicate the fact that systems analysis is performed during many, if not all, subtasks. The study management, E39, subtask is separated from the normal process flow to indicate the planning/management aspects of that activity.

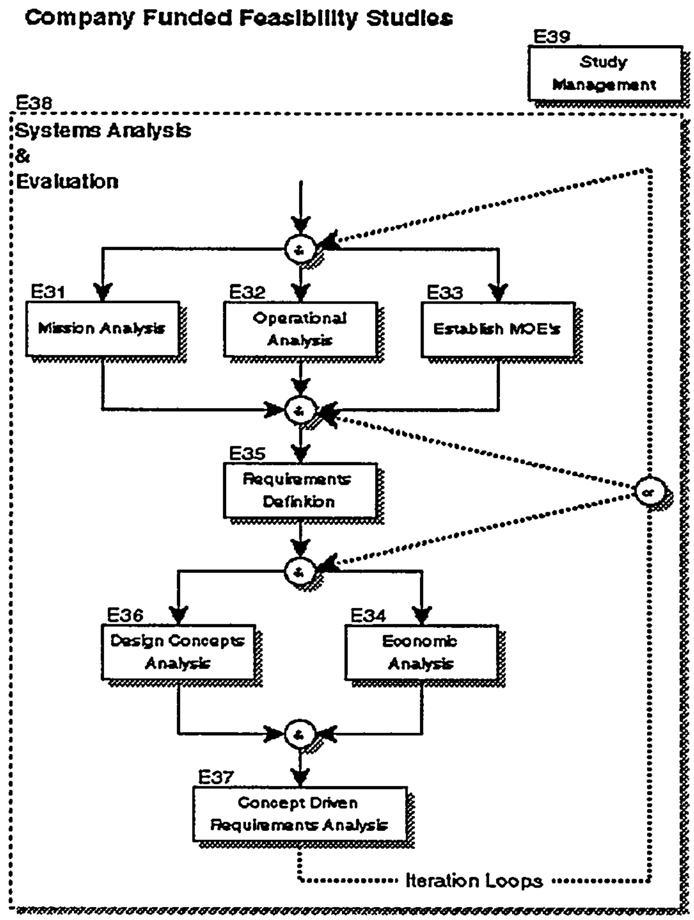

FIGURE 2. Company funded feasibility studies subtasks.

The scope of this study did not permit an economic analysis to be performed. Under normal circumstances, the study should have provided a concept down select based on the measures of effectiveness from which concept requirements could have been developed. The process delineated in Figure 2 is an iterative process which builds on the results of each of the other elements associated with the task. The remainder of this study will address the eight subtasks delineated in Figure 2 to varying degrees of detail. The operational analysis was considered along with the functional analysis in the requirements sections.

2.0 Mission Analysis

An approach different from standard nuclear weapon design was taken for the mission analysis of these systems. The first step was to change from a paradigm of design driving the mission to one in which missions drive the engineering design. Examination of the strategic target databases provided information which can be used to generate concept requirements. Statistical techniques provide insight into weapon system accuracy requirements, damage mechanisms, area of effect requirements, penetration requirements, sensor requirements, and timing requirements to mention a few. The 1993 "Summer Study" provided insight into potential target sets.

The study has, however, been driven in the direction of assessing the classes of targets which may be successfully attacked by a handful of weapon concepts. As often happens, the mission is not driving the technology. The figures which follow provide a feel for a subset of strategic targets which need to be held at risk by conventional weapons

Figure 3 and Figure 4 provide views of a thermal power plant. Detailed examination of the plant and site layout enable a design engineer to set accuracy requirements, damage mechanisms, and range-of-effect requirements. Detailed analysis of the potential targets results in categories of targets which can be used to define classes of system requirements. Selecting a small, representative target set with specific layouts, hardnesses, and distribution to define weapon system requirements will result in system designs which are optimized for a particular target set. That approach will result in a severely restricted mission capability.

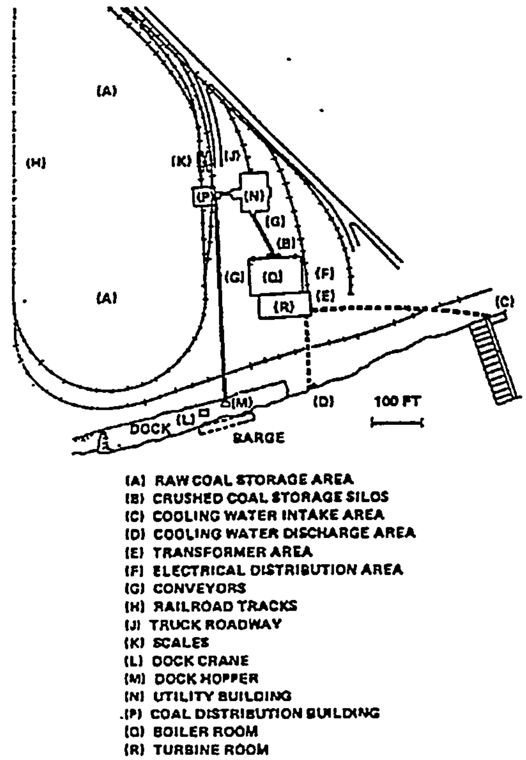

FIGURE 3. Site layout for a conventional power plant.

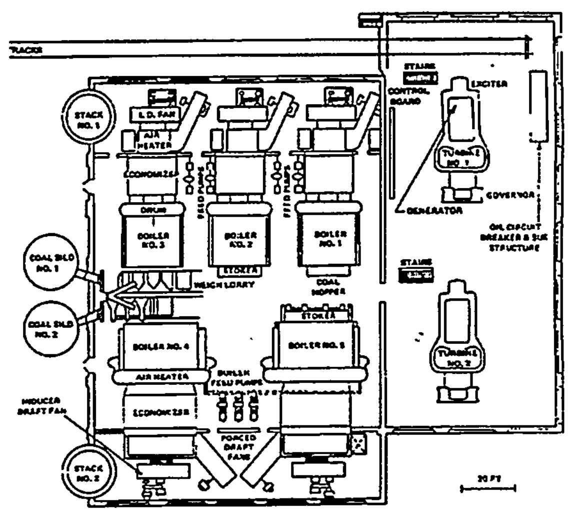

FIGURE 4. Generic boiler / turbine room layout.

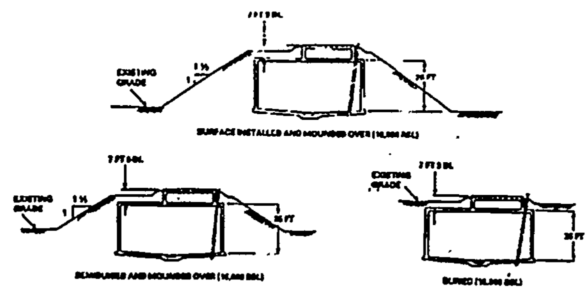

FIGURE 5. Examples of POL storage facilities.

Figure 5 provides some configurations for the storage of petroleum, oil and lubricants (POL). These configurations are associated with military storage, i.e. hardened and shallow burial. Commercial storage would not produce a different set of system requirements.

Figure 6 was developed for the 93 Summer Study and provides consensus information for what shallow buried bunkers might look like. Figure 6 clearly shows the difficulties that may present themselves in defining systems requirements for mitigation of this type of target.

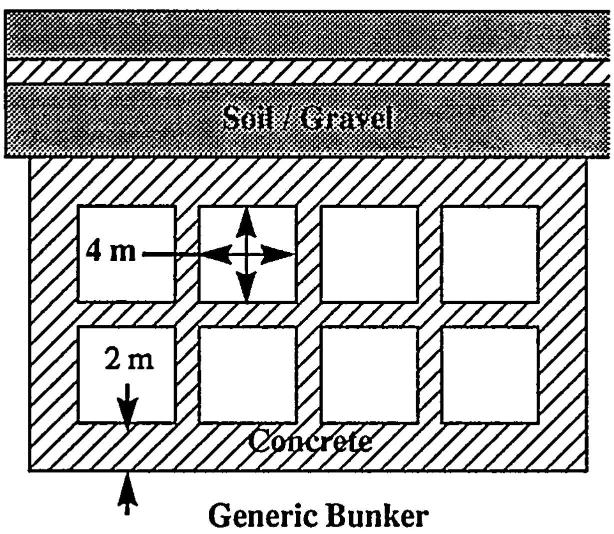

FIGURE 6. Shallow buried bunkers and command posts.

Much of the consideration has been along strategic lines. This constraint may have to be relaxed in the changing world order; we may have to use these weapons on less traditional missions such as tactical support;, for political demonstration missions. Providing a system with broad applicability enhances the systems political survival and utility far into the future. Missions should be subdivided into strategic targets, tactical targets, and political targets, with miscellaneous targets covering what is left over.

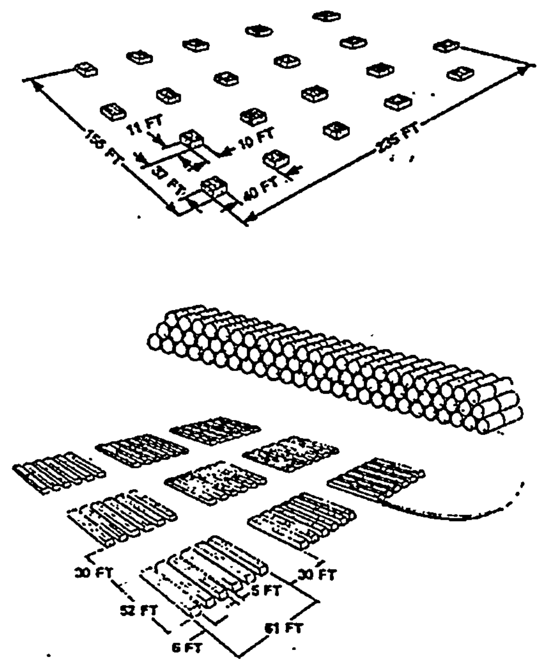

FIGURE 7. Storage dump for POL type materials and ammunition.

Examination of the different target classes and the potential disruption and destruction mechanisms for each; reveals a pattern which can be used to develop MOEs. These MOEs are developed for use in the systems engineering design analysis. Most targets are protected by steel, armored shells/casings, concrete, dirt, rubble beds, or combinations of these materials. The classical objective is to either penetrate to the vulnerable area and deliver a package which will cause damage or to project a damage mechanism to the targets. If we can identify damage mechanisms or penetration techniques to deliver damage potential, it becomes reasonable to develop fragility curves for use in the engineering design analysis.

2.1 Damage Mechanisms

Preliminary analyses were conducted to assess the potential impact of a number of system and subsystem design factors on mission performance type MOEs. Esoteric concepts were considered in the initial phases to determine their utility as kinetic energy (KE) enhancement mechanisms. These concepts ranged from high explosives, fuel-air, detonate-able powders, hydrogen-oxygen detonation phenomena as well as the employment of pyrophoric materials.

Early studies indicated that there were significant dispersal problems associated with the detonate-able powders as well as the fuel-air concepts. The amount of chemical energy available would provide reasonable damage enhancements while being efficient from the perspective of not having to transport oxidation material. The problem with these concepts is the ability to efficiently disperse the fuel material at the target location.

The hydrogen concept appeared attractive from a chemical energy content perspective and a fuel dispersal perspective. The chemical energy per Kg of fuel is about an order of magnitude greater than that of a high explosive (HE). The difficulty with this approach involves the ability to carry sufficient quantities of hydrogen to the target site. The high pressure reservoir or a metal hydride approach did not permit sufficient quantities to be transported.

A sensitivity analysis was performed to acquire a better understanding of the effects on damage potential of a number of basic design factors. The sensitivity analyses consisted of two phases. The first phase examined the effects on damage potential of kinetic body geometry, velocity, impacted material and a limited set of enhancement mechanisms. The enhancement mechanisms included detonate-able material as well as material which could transition into a deflagration regime. The damage mechanisms considered included local ground shock as well as overpressure.

The cost of the calculations and the number of factors being considered led us to pursue a design-of-experiment approach for assessing sensitivities. An L9 orthogonal matrix was selected as the design matrix in which four factors could be assessed at three levels. The matrix initially proposed is provided in Table 1. The objective was to run a nine calculation experiment from which we could assess the effects of the four factors. As indicated the four factors consisted of impacting velocity, body geometry, impacted material conditions and the chemical potential of the impacting body material.

TABLE 1. Experimental design matrix for use in preliminary sensitivity analysis.

Exp. #	Velocity	Reaction	Geometry	Surface
1	8 kft/s	Inert	Sphere	Concrete
2	8 kft/s	Defalgration	Plate	Soil
3	8 kft/s	Detonation	Cone	Ocean
4	12 kft/s	Inert	Plate	Ocean
5	12 kft/s	Defalgration	Cone	Concrete
6	12 kft/s	Detonation	Sphere	Soil
7	16 kft/s	Inert	Cone	Soil
8	16 kft/s	Defalgration	Sphere	Ocean
9	16 kft/s	Detonation	Plate	Concrete

2.1.1 Overpressure Damage Potential

Early calculations indicated that overpressure shock generated during impact would not provide sufficient energy to produce requisite levels of damage in a target. At ranges of interest, the overpressures were on the order of 10's of psi. This is not sufficient to provide the type of damage required for a weapon system of this class. In terms of local ground shock, we found that the detonation of the impacting body actually degraded the extent of the stress contours into the target region.

The contours shown in Figures 8 and 9 show the differences in maximum extent of the overpressure contours. The difference in maximum extent was on the order of 1.0 meter. The total extent of these overpressure contours amounted to approximately 2.0 meters. This provides a basis for saying that overpressure and dynamic pressure are not suitable damage mechanisms for a kinetic weapon with or without a HE enhancement.

2.1.2 Ground Shock Sensitivity Analysis

The calculations also indicate that not only does a HE payload for the kinetic energy body not improve damage potential, it actually degrades damage effectiveness. Figures 8 and 9 show the difference in radial and axial extent of the 0.5 and 0.1 kilo-bar stress contour into the impacted medium.

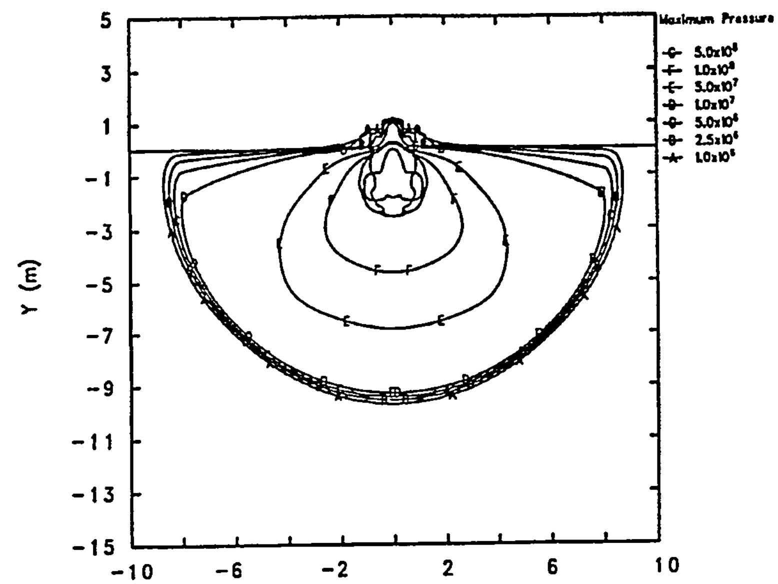

FIGURE 8. Inert sphere impacting the ocean.

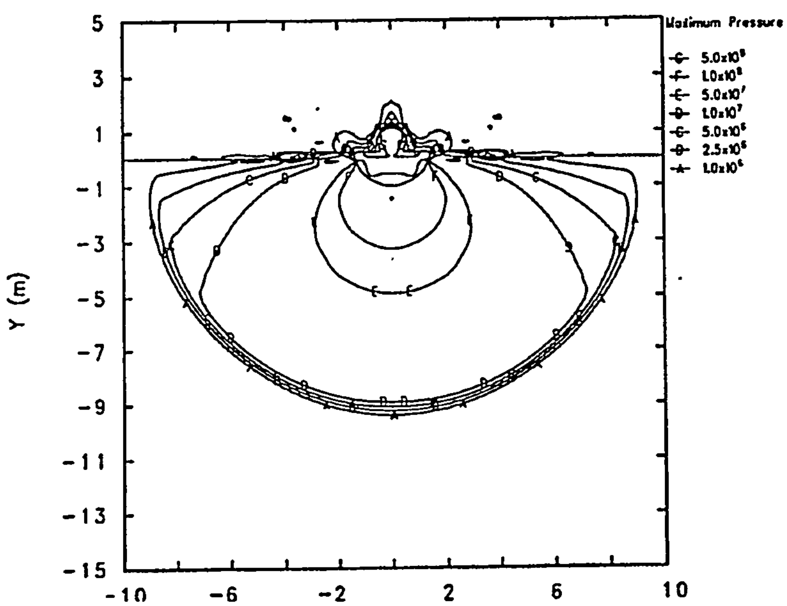

FIGURE 9. Detonating sphere impacting the ocean.

These curves are annotated as curves G and F, respectively, in the figures. The conclusion reached for this effect was due in part to the explosive mitigating a significant portion of the body's kinetic energy. The detonation, being isotropic, resulted in significant amounts of energy being directed away from the principle axis of impact.

To simplify the CTH calculations, the analytical experiments were modified due in part to the results of the detonation assessments. Experiments which were intended to assess deflagration effects were modified and assumed to be inert impacting bodies. This reduced the amount of information acquired from the sensitivity calculations.

The indirect damage potential objective function used to determine the effects of the limited set of design parameters was a volume of effect for either the 0.5 or 0.1 kilo-bar stress contour. Figures 10 and 11 provide insights into the degree of influence on damage potential for each design factor. These metrics do not define absolute levels of effect, rather they provide a comparison of potential effect between the design parameters.

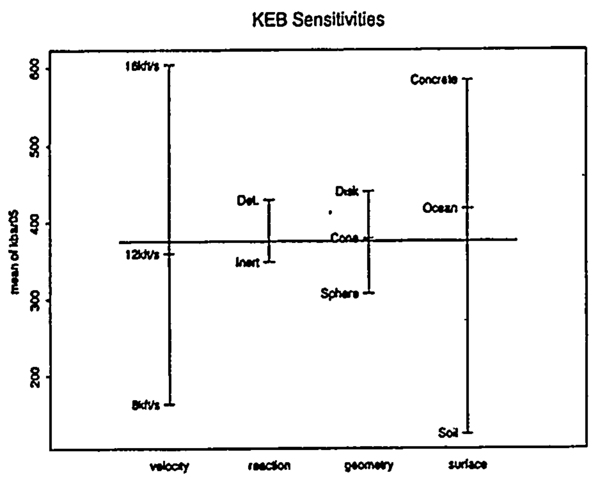

FIGURE 10. Sensitivities of design factors on the 0.5 kilo-bar stress contours.

What can be seen is that the principle factors affecting performance is impact velocity and the impacted medium. The chemical content and the geometry are not dominant design factors. The 0.1 kilo-bar case indicates that impacted medium is the single most important factor in performance.

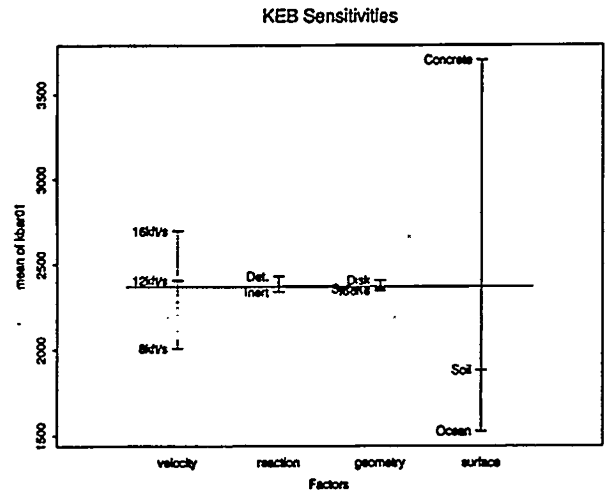

FIGURE 11. Sensitivities of design factors on the 0.1 kilo-bar stress contours.

The studies did not address the effects of layered media or media with typical porosity characteristics. The porosity of an impacted medium has the effect of absorbing a significant fraction of the body's kinetic energy. Additional studies performed by P. Yarington et al. demonstrate these phenomena quite clearly. This effect must be considered in any weapon design concept which is intended for use against subsurface targets.

Rod penetration studies seem to indicate that, once a projectile has reached hydrodynamic conditions, the projectile achieves conditions which may not be as detrimental in porous media as we think. These ablation phenomena have been parametrically functionalized to the ratios of the impacting and impacted material densities. The velocity of the impacting body is not severely degraded during the penetration phase.

This may provide a design loophole to allow the bulk of the kinetic energy to be transferred to the buried target.

2.1.3 Deflagration Effects

Early calculations for detonating bodies indicated that the chemical energy associated with HE was insufficient to enhance the damage mechanisms associated with KE weapons configurations. As a result of this preliminary analysis no calculations were performed which examined a pyrophoric/KE hybrid weapon. However, deflagration resulting from pyrophoric materials may prove useful against certain target classes. These targets include POL storage, ammunition dumps, and some urban industrial (UI) type targets.

There is a secondary effect which will be examined later in this document. The potential energy available in a thermite type material may prove useful in antipersonnel applications. There have been numerous experiments conducted for the power industry in which molten materials, typically produced through some thermite reaction, were dropped on concrete structures to ascertain erosion rates and characteristics.

2.1.4 Pyrophoric and Aerodynamic Heating Analysis

The trajectories developed in the last section for CEP enhancements were also assessed for aerodynamic heating effects. The submunitions were assumed to be constructed from either magnesium or depleted uranium, both pyrophoric materials. The issue being addressed in this analysis concerned the possibility of pyrophoric ignition due to aerodynamic heating.

The detailed thermal analysis performed by D.L. Potter is included in Appendix A the sensitivity analysis is presented in Figure 12. In all cases, aerodynamic heating of pure pyrophoric materials was insufficient to ignite the material under normal conditions. Coating the pyrophoric in thermite may produce the desired aerial ignition. Additionally, impact should provide sufficient energy to ignite the pyrophoric material.

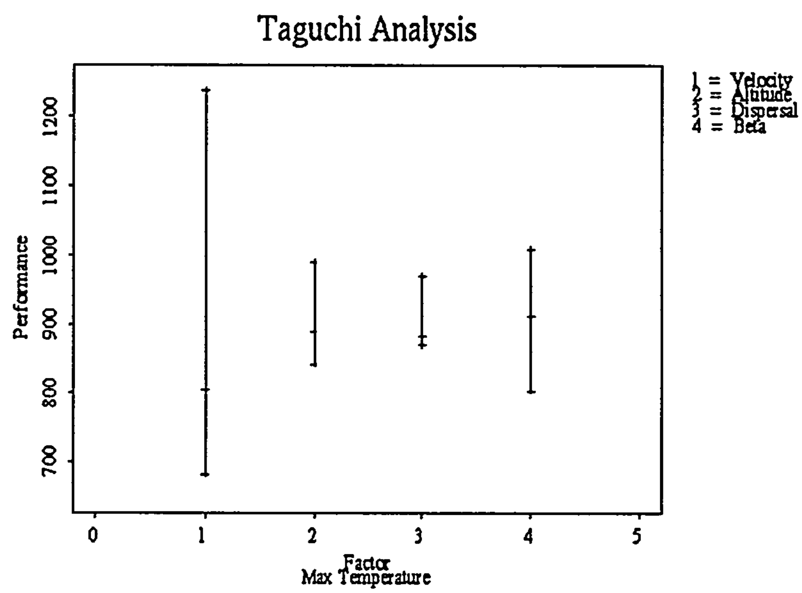

FIGURE 12. Sensitivity of aerodynamic heating to selected design factors.

2.1.5 Penetration Analysis

The analysis described early in the report showed that at this stage of design analysis, geometry is not a strong player in the design process. A balanced approach must be taken to assess the requirements of all elements of the weapon system and the interactions and correlations that each subsystem plays in achieving an overall system performance. As a design process progresses additional detail must be included in the process in order to identify an optimal design within the constraints that have been defined through the requirements analysis process.

The sensitivity study conducted early in the analysis showed, among other things, that the geometric shape of the penetrating body was only slightly more important than the criteria associated with inert or detonating warheads. Figure 10 presented information indicating that the important factors at this stage of the analysis are velocity of the impacting warhead and the media being impacted. It should be remembered that the impacted media is assumed to be semi-infinite in extent. These criteria are relaxed in later analyses.

Significant study has been conducted in the areas of hydrodynamic impact phenomena. A nice piece of work was performed by Hohler and Stilp (Hohler 1987) on hyper-velocity impact of long rods with a length to diameter (L/D) ratio of 1-32. This information was used in the study by considering cylinders of varying L/D for use in the follow-on mission analysis. In their paper they discussed a number of interesting phenomena. Their discussion included saturation velocities, optimal penetration depths vs. velocity, density ratio effects, and the effect of L/D ratio.

Penetration phenomena can be broken into four basic phases, the transient phase, the primary phase, the secondary or cavitation phase and the recovery phase. In each of these phases, the physics of the phenomena are different. The heuristic correlations often used do not distinquish between the different phases. Hohler and Stilp did propose correlations that identify separate effects from the different phases. From their model discussion it appears that the secondary phase is the easiest phase to describe analytically.

The correlations of interest include the saturation condition, which corresponds to an asymptotic penetration depth that is independent of velocity. When velocities are greater than the saturation velocity, the penetration depth can be defined as:

$$P = L \cdot (\rho_p / \rho_T)^{0.5} \qquad \text{(EQ 1)}$$

There appears to be a phenomenon associated with penetration mechanics in which there exists an optimal velocity for penetration when the penetrated strength is greater than the target material strength. There was not a great deal of discussion of the phenomenon, but it might be worth pursuing to determine if advantage might be taken of this effect.

For very low L/D (L/D ~ 1) ratios, the authors indicated that the relationship between depth of penetration and velocity is proportional to $(V_p)^{2/3}$, where V_p is the projectile velocity. The secondary phase of penetration phenomena is directly proportional to the L/D ratio, with the effect being an increasing depth of penetration for increasing L/D.

3.0 Measure of Effectiveness (MOE)

The very different damage characteristics associated with kinetic energy weapons necessitates that a reassessment of typical nuclear damage paradigms be performed. We have in the past operated with the luxury of knowing that the systems we were designing could achieve mission success with margin to spare. The limited effects we see associated with these new strategic concepts require far greater analytic detail. Damage expectancy calculations, and Pssk calculations need to be tempered with greater statistical detail. Targets must be treated as area targets as opposed to point targets. We also need to consider force level effects in much greater detail in order to assess and optimize weapon system designs.

The MOEs delineated in this section are the result of an iterative process between the mission analysis discussed above and the system requirements analysis delineated below. The initial CTH analyses provided insights into velocity and geometry considerations for a KEW design, which identified additional information that was needed to perform a more detailed mission analysis. This paper took the iterations to a point where Phase I and II levels of system detail were achieved.

3.1 Uncertainty/Noise

Experience has shown that most, if not all, design is approached from a deterministic perspective. This approach, while tractable for many engineering efforts, does not reflect the physical realities of modern complex design problems. There need to be methodologies in place that can treat design as the stochastic problem it is. There are a great many uncertainties and variabilities associated with the missions, ultimate utilization, production variabilities, and simple environmental unknowns.

The systems engineer needs to understand and identify these factors for consideration in any design analysis performed. This provides the foundation for design risk mitigation, an essential element in robust design efforts. The uncertainty analysis is most extensive in the early design phases of a project; as detail is added through the various phases of the design effort, some of the variability can be reduced. However, it is not possible to remove all of this variability even in the final development stages of a system design.

Strategic weapon system design is the most demanding design activity in terms of noise analysis. The service life required of these systems severely taxes the design engineers' prognostic capabilities. Therefore, far greater emphasis needs to be placed on mission and requirements analysis for these systems.

The scope of the problem being addressed in this study was fairly limited. As a result the uncertainties and noise that were considered included: target uncertainties, subsystem performance parameters, operational factors, force level considerations. Within this framework we need to recognize that potential adversaries can arrive at vulnerability estimates of their facilities/capabilities and make adjustments that may mitigate some of our concepts.

Target uncertainties are the dominant area of variability in the design problem. From a nuclear design perspective, we needed to know where a facility was located in order to assess its vulnerability. When considering conventional systems, we need to know a great deal more about the target since the target will have to be considered an area target as opposed to a point target. The geological factors become more critical as well as the details of the target. The targeteer needs to know locations of the vulnerable areas within a target. From a perspective of mission success, the reconstitution capability as well as bomb damage assessment become design issues.

The effect of subsystem accuracies must be considered in the analysis of weapon systems. Target lethality is typically nonlinearly dependent on proximity to the target. Understanding system performance variabilities and employing methodologies that attempt to mitigate the consequences of these uncertainties are paramount to the success of the design effort. Along similar lines, the context of the force structure in which a new weapon system will be used impacts the design. The reality of modern design is that a single system is not a credible answer, rather an integrated application of diverse systems is needed to solve the difficult missions.

The analyses used in this study attempted to fold as many factor variabilities and noise parameters into the problem to identify requirements as needed to be placed on a conventional system in order to produce a credible conventional concept. Resource limitations did preclude some uncertainties from being included in the analyses.

3.2 Fragility Curves

The preliminary mission analyses provided insights into potential damage mechanisms for consideration in these studies. The approach used in typical analyses did not seem appropriate to this study, in particular, the lethality aspects of the mission analysis. It was felt that the concept of fragility analysis could provide a framework to be used in system level performance assessments. Fragility curves in general capture the response of a system to the application of some predefined force. In this case the response was the targets ability to survive the application of damage mechanisms associated with kinetic energy weapons (KEW).

The fragility curves were generated for two damage mechanisms, penetration, and overpressure of 1.0 Kilo-bar and two types of generic target. The target types consisted of buried bunkers, which would look something like the generic bunker in Figure 6 . Another was a first look at the possible use of KEW for chemical/biological weapons (CBW) destruction. Fragility curves were not generated for consideration in armored types of targets. At this time the bunker appeared to be the most stressing mission requirement. The information for use in creating the fragility curves was generated using the CTH hydrodynamic code. Capturing the noise associated with the problem was handled using techniques developed by Taguchi as explained by Phadke (Phadke, 1990). The L18 orthogonal matrix was selected for use in the experimental design setup. The factors examined included velocity, projectile size, projectile length to diameter ratio, soil yield strength, soil type, the concrete parameters JHS2 and JHP2, and a layering parameter to assess the analysis uncertainties. The two concrete parameters are used to define the nonfailed yield strength of the concrete (ref. CTH manuals). The CBW fragility curves were far less extensive but were created to provide a quick vulnerability look. The levels used in the analysis are provided in Table 2.

The data generated from the CTH calculations were then used as example data in a neural program to provide a predictive lethality capability. The neural net employed in this predictive system was a feed-forward back propagation network. This type of net predicts parametric outputs based on predefined factors and is trained via an iterative error correction mechanism that distributes the training errors regressively through the net until the network achieves satisfactory performance.

TABLE 2. Factor Levels used in the fragility analysis.

Factor	Level 1	Level 2	Level 3
Layering	10/20 cm	30/60 cm	
Velocity	5 kft/s	15 kft/s	25 kft/s
Size	2 cm	5 cm	10 cm
L/D Ratio	1	5	10
Soil	aneos 7122	Kaolinite	Crushable quartz
Yield	0.2 e8	0.5e8	0.2e9
JHS2	420e7	470e7	520e7
JHP2	700e7	1250e7	1800e7

Table 3 is the orthogonal matrix defining the combination of levels for use in the fragility analyses.

TABLE 3. L18 orthogonal matrix used in fragility analysis.

Exp. #	Layering	Velocity	Size	L/D Ratio	Soil	Yield	JHS2	JHP2
1	1	1	1	1	1	1	1	1
2	1	1	2	2	2	2	2	2
3	1	1	3	3	3	3	3	3
4	1	2	1	1	2	2	3	3
5	1	2	2	2	3	3	1	1
6	1	2	3	3	1	1	2	2
7	1	3	1	2	1	3	2	3
8	1	3	2	3	2	1	3	1
9	1	3	3	1	3	2	1	2
10	2	1	1	3	3	2	2	1
11	2	1	2	1	1	3	3	2
12	2	1	3	2	2	1	1	3
13	2	2	1	2	3	1	3	2
14	2	2	2	3	1	2	1	3
15	2	2	3	1	2	3	2	1
16	2	3	1	3	2	3	1	2
17	2	3	2	1	3	1	2	3
18	2	3	3	2	1	2	3	1

The results of the calculations are provided in Figure 13 and Figure 14 . The plots show the importance of the various contributory factors to damage potential of a generic target. The plots indicate that, aside from the design parameters of velocity, penetrator size and aspect ratio, soil type is the next most important factor. The remaining parameters are considerably less important. The performance against a target can only be approximated if detailed intelligence of the soil conditions in the neighborhood of the target is lacking. A superior design approach is to identify systems that can mitigate the impact of this inherent uncertainty. A system with greater velocity potential might compensate for the noise associated with the mission.

Figures 13 and 14 provide evidence that the attempt to create a continuous medium for comparative analysis was achieved. The high resolution calculations used a 10 cm by 20 cm layering of concrete and soil. The low resolution calculation used a 30 and 60 cm layering scheme. The remaining factors used in the analysis examined the importance of penetrator velocity, penetrator L/D ratio and size, soil models, and yield, and two parameters used in the concrete models.

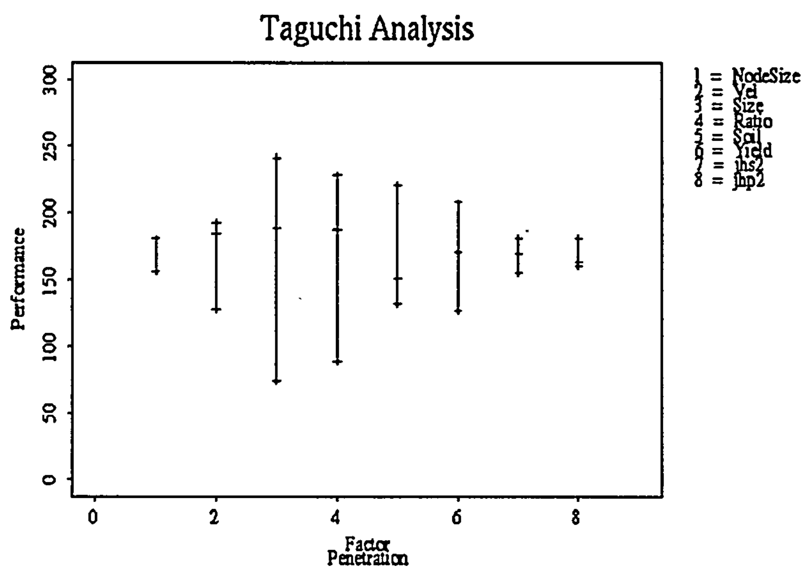

FIGURE 13. Sensitivity analysis for penetration damage mechanism.

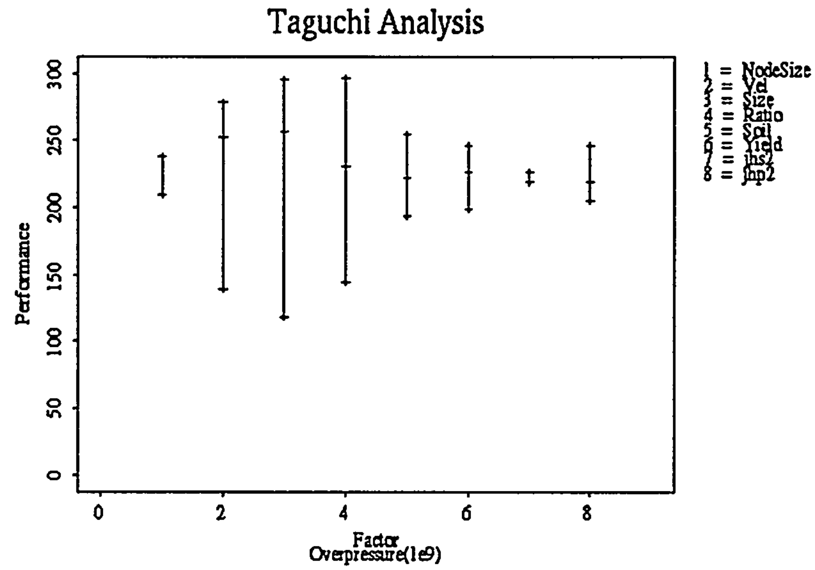

FIGURE 14. Sensitivity analysis for 1.0 Kbar overpressure damage mechanism.

Figures 15 and 16 demonstrate the predictive capability of the trained neural net. This function, when used with system level analyses provides the design engineer with the information needed to find a concept satisfying mission requirements. The neural net has been constructed to predict performance as functions of velocity, L/D ratio and size. The figures represent performance against a composite media consisting of soil and concrete, with an L/D =5 aspect ratio.

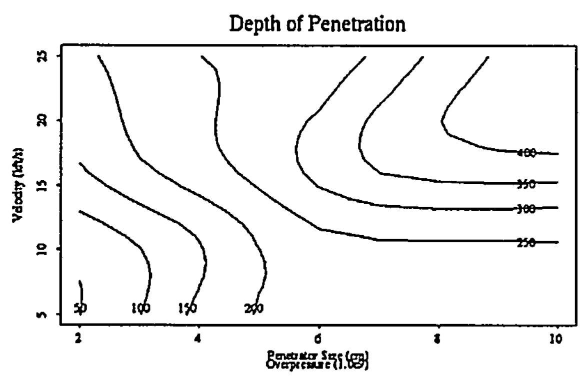

FIGURE 15. Contour map of overpressure (1.0e9 d/cm2) penetration into composite media.

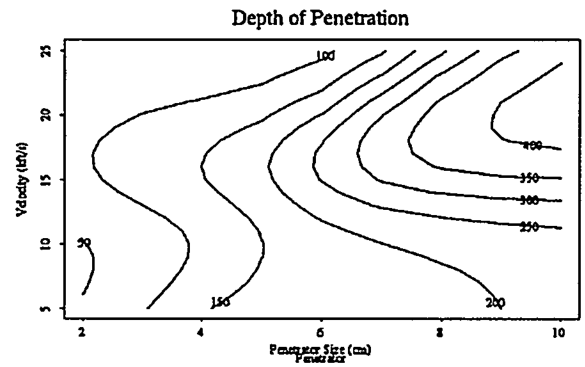

FIGURE 16. Contour map of penetrator penetration into composite media.

The information captured in the neural net provides more detail than is immediately needed. The analyses that follow utilize a fraction of the information depicted in the figures. The first step of the analysis was to define the probability of target damage as a function of velocity. A broader utilization of the information captured in this first neural net requires a larger suite of calculations to add fidelity to the statistical parameters in the models. The smaller model provided a perspective on the benefits that can be derived from an analysis employing these technologies.

A second suite of calculations was performed to assess the vulnerability of targets protected by steel or some type of metal jacket, for example turbine housings, oil tanks, or armored vehicles. Figure 17 assumes that the damage mechanism is penetration by a tungsten rod with varying characteristics.

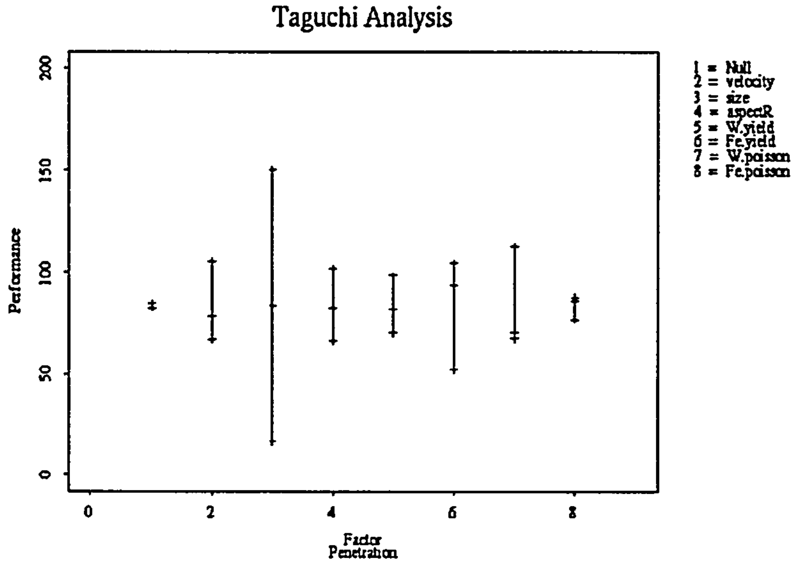

FIGURE 17. Sensitivity analysis of plate penetration by tungsten projectiles.

The factors and levels used in the analysis are listed in Table 4.

TABLE 4. Factor Levels used in the fragility analysis.

Factor	Level 1	Level 2	Level 3
Layering	10/20 cm	30/60 cm	
Velocity	5 kft/s	15 kft/s	25 kft/s
Size	2 cm	5 cm	10 cm
L/D Ratio	1	5	10
W Yield	50e9	45e9	55e9
Fe Yield	6.0e9	5.4e9	6.6e9
W poisson	0.25	0.28	0.31
Fe poisson	0.25	0.28	0.31

Some results of the trained neural net are presented in Figure 18. The aspect ratio used in the analyses was 5.0.

The model to be used in later sections assumes that the phenomena, i.e. penetration, is solely a function of velocity. This held the requirements analysis to a level that avoided design specific details. The information generated and displayed in the previous figures was used to approximate the statistics needed in the model. The approximation will mitigate the inclusion of L/D ratio and penetrator size from being included in the sensitivity analyses of the later sections. This information can be useful for assessing the relative importance of this design parameter. The deduced model permits us to approximate the classic S-shaped curve characteristic of fragility curves. The estimated standard deviation and mean penetration depth provide the systems engineering analyst with probability estimates of penetration to target depth.

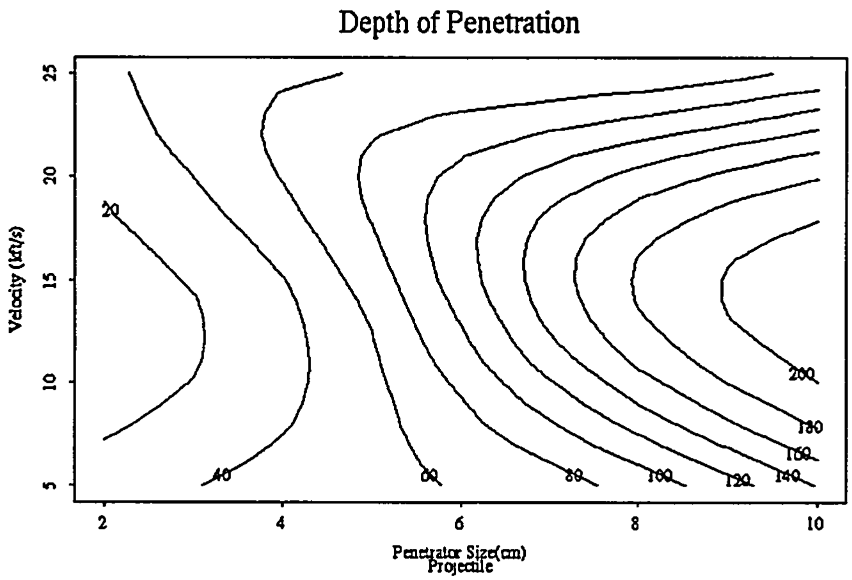

FIGURE 18. Data generated by a trained neural net showing the velocity and penetrator size dependencies at an aspect ratio of 5.0.

3.3 Conventional Strategic MOE

The MOE developed, which is the probability of killing the target (P_{Kill}), must capture the statistical nature of the problem as well as account for the various uncertainties in the problem. The model used in much of the analysis is provided in Equation 2.

$$P_{Kill} = P_{Hit} \cdot P_{CrA_{Hit}}(CrA_{Hit}|Hit) \cdot P_{Fire} \cdot P_{FKill}(FKill|CrA_{Hit}) \quad \text{(EQ 2)}$$

In this expression P_{Hit} is the probability of a weapon hitting the target. The second term, P_{CrAHit} (CrA_{Hit} | Hit), is the probability of hitting a critical area of the target given that you hit the target. P_{Fire} is the probability that the system will detonate, and $P_{FKill}(F_{Kill}$ | $CrA_{Hit})$ is the probability that the target will be "killed" given that you hit the critical area of the target and the system detonates. The term P_{Hit} is defined by Equation 3.

$$P_{Hit} = A_{Dl} \cdot P_{Abl} \cdot A_{Abl} \cdot P_{Mbl} \cdot A_{Mbl} \cdot P_{Dprb} \cdot A_{Dprb} \cdot P_{Alrb} \cdot A_{Alrb} \cdot P_{Mlrb} \cdot A_{Mlrb} \cdot P_{Alwh} \cdot A_{Alwh} \quad \text{(EQ 3)}$$

Variable definitions are provided in Table 5.

TABLE 5. Variable definitions.

Variable	Definition
A_{Dl}	Accuracy of delivery.
P_{Abl}	Pr of assessing the buss location.
A_{Abl}	Accuracy of measuring the bus location.
P_{Mbl}	Pr of modifying the bus location.
A_{Mbl}	Accuracy of modifying the bus location.
P_{Dprb}	Pr of deploying the reentry bodies.
A_{Dprb}	Accuracy of deploying the rb's.
P_{Alrb}	Pr of assessing the location of the rb's.
A_{Alrb}	Accuracy of locating the position of the rb's.
P_{Mlrb}	Pr of modifying the location of the rb's
A_{Mlrb}	Accuracy of modifying the location of the rb's.
P_{Alwh}	Pr of assessing the location of the warhead.
A_{Alwh}	Accuracy of assessing the location of the warhead.

4.0 Requirements Analysis

Design for a specific target or a couple of targets can result in a system that may not satisfy a tactical mission. The design process must identify the range of missions and associated uncertainties of these potential missions. This is needed to ensure that the culmination of the design process results in a concept satisfying the broader tactical mission. Figure 19 shows the implication of poorly defined target-set requirements. The 45-degree line is an indicator of system capability and mission requirements. A design with performance along this line is the goal of the system designer. When a specific case is identified as the metric for design success, a situation may occur in which the performance curve may look like the dotted line in the figure. Under these conditions, the system possesses suitable performance at the design point but substandard performance against other points in the design curve. A design will not likely follow the 45-degree line but will more likely be represented by the solid curve which indicates system performance more acceptable across a broader spectrum of missions. Another approach would be to identify widely divergent point missions to increase the likelihood of a globally suitable concept.

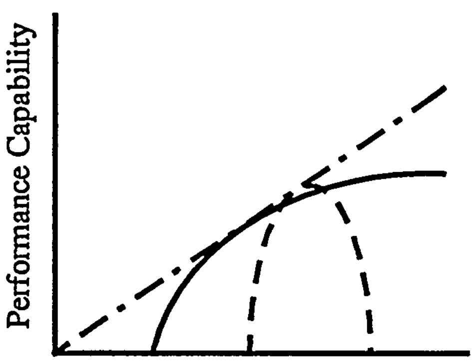

FIGURE 19. Performance vs. mission requirements diagram.

4.1 Trident II Constraints

Within the context of this study, the set of constraints being imposed are based on the use of the Navy fleet ballistic missile (FBM) as the delivery system and existing reentry body (RB) shells as the delivery vehicles for the conventional strategic warheads. Developing concepts within these constraints imposes geometric and weight and balance constraints on the system concepts that are consistent with existing warhead systems. Ballistic analysis would provide limits on weight based on flight stability, and RB envelope constraints. Material constraints are more fundamental; for example, avoid materials which react exothermically when in contact with water. The operational nature of a FBM necessitates these types of constraints. Similarly, the use of an existing delivery system and RB imposes range constraints on concept requirements that match characteristics of existing weapon systems.

The interface constraints need to be developed in conjunction with the operational arm of the Navy. There needs to be consideration of the utilization objectives of the operational Navy. Issues of fire control software, targeting goals and objectives and intelligence opportunities should also be factored into any concept developed.

For classification reasons the weight, balance, and geometry constraints were not included nor were range and flight characteristics. The operational considerations have not been included because of resource limitations in performing the study. If there is interest in the approach being employed in this study, additional constraints can be implemented that reflect the operational constraints identified through a more detailed interaction with the operational arm of the Navy.

4.2 Functional/Operational Analysis

A high level functional analysis was performed in order to provide foundations from which system concepts might be developed. The constraints imposed were based on a premise that the weapon system would be delivered via a ballistic missile system. All concepts had to adhere to these basic restrictions. Figure 20 provides a view of the system functions which need to be performed in order to achieve the mission requirements.

Block 5 in Figure 20 is examined in slightly greater detail. Fgure 21 was used to develop the mathematical model for the MOE defined in the earlier sections.

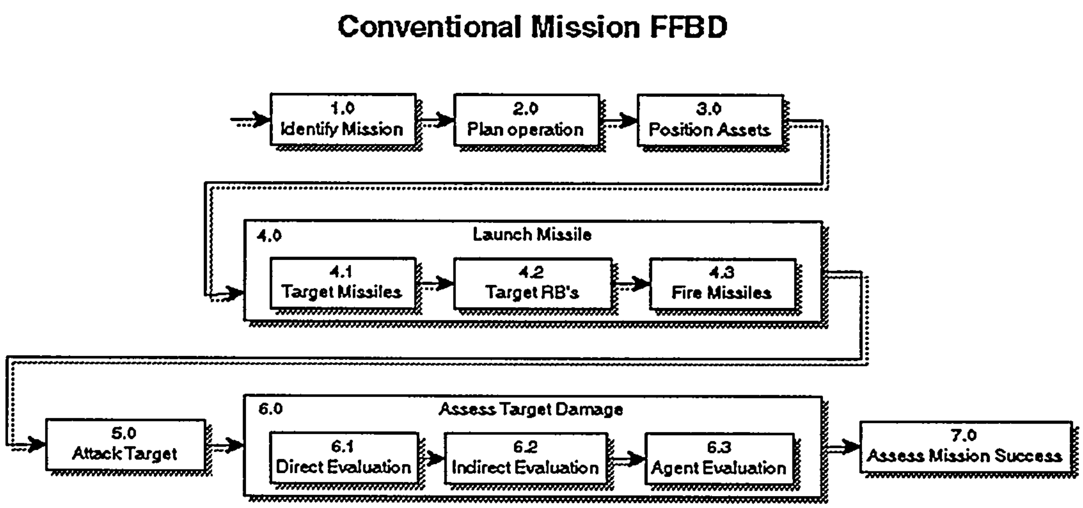

FIGURE 20. Generic ballistic missile delivered conventional block diagram.

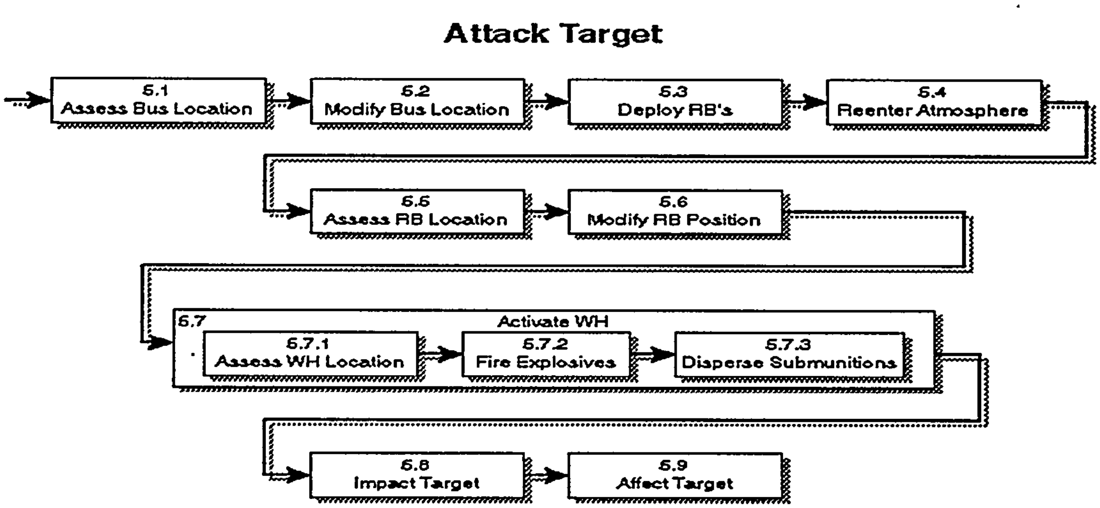

FIGURE 21. Generic attach functional block diagram.

4.2.1 Dispersion Analysis

The second phase of the analyses examined dispersal phenomena. The design factors assessed consisted of dispersal velocity, altitude, density, and the beta of the body. These analyses were performed to assess the potential for improving the CEP of the KE weapon system

Similar to the previous design of experiment, an L9 orthogonal matrix was used to define the combination of design factors to enhance computational efficiency. The matrix of experiments is displayed in Table 6.

The dispersion calculations were performed by calculating the trajectory of 5 spheres for each experiment with the AMEER code. The analysis consisted of giving four of the spheres a velocity in the radial direction at the altitude defined by the experiment. Each of the four spheres were directed at equally spaced angles about the fifth sphere, which was allowed to follow the nominal trajectory.

TABLE 6. Experimental design matrix for use in the dispersion analysis.

Exp. #	Velocity	Altitude	Velocity(R)	"beta"
1	8 kft/s	100ft	50 ft./s	A
2	8 kft/s	550ft	100 ft./s	B
3	8 kft/s	2000 ft.	250 ft./s	C
4	12 kft/s	100 ft.	100 ft./s	C
5	12 kft/s	550 ft.	250 ft./s	A
6	12 kft/s	2000 ft.	50 ft./s	B
7	16 kft/s	100 ft.	250 ft./s	B
8	16 kft/s	550 ft.	50 ft./s	C
9	16 kft/s	2000 ft.	100 ft./s	A

A ~ 29.5 kg/m2

B ~ 322.6 kg/m2

C ~ 1935.5 kg/m2

The post trajectory sensitivity analysis results are displayed in Figure 22.

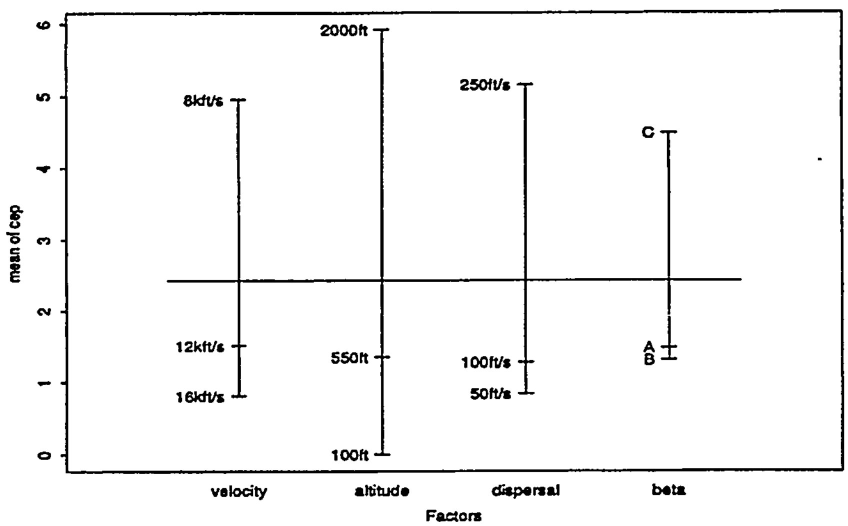

FIGURE 22. CEP enhancement sensitivity analysis.

We find that high density bodies dispersed at large deltas in velocity and significant altitudes are required in order to generate dispersions of interest.

4.2.2 Kinetic Energy Degradation

A secondary aspect of this dispersion analysis involved the loss of kinetic energy resulting from the less efficient beta of the submunitions. Aerodynamic drag will result in loss of kinetic energy with a transfer to air and body surface heating. Heat transferred to the air is lost as a contributor to target damage. The surface heating could potentially be used by the weapon system through indirect effects. The velocity degradation effects can be seen in Figure 23 .

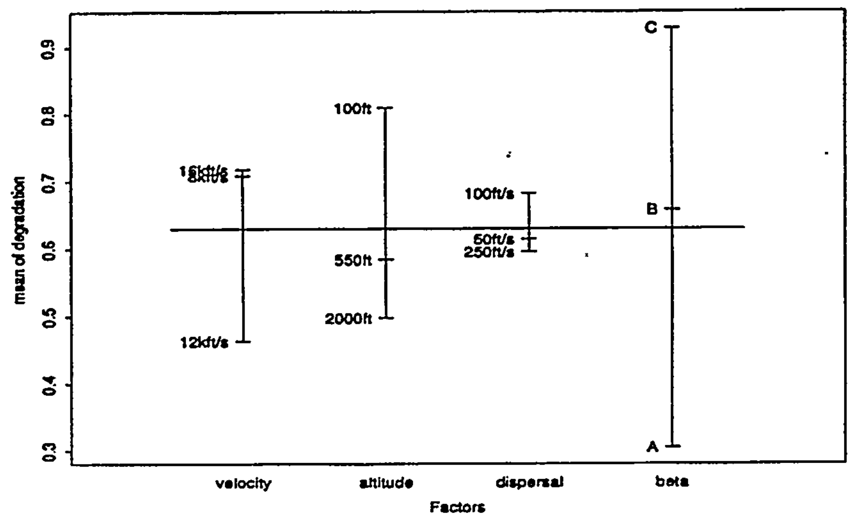

FIGURE 23. Velocity degradation analysis.

The chart shows that beta(W/C_{DA}) is the dominant factor associated with velocity degradation. The radial velocity has little effect on the velocity degradation. These plots demonstrate one effect which the analyst needs to be cognizant of, that is "confounding effects" associated with design of experiment analysis. Many times we find that factors interact with each other, either negatively or positively. The result is slightly ambiguous results for the primary effects of each of the factors. One way to mitigate this problem is to avoid setting a factor to each column of the orthogonal matrix. Our situation has been slightly confounded but we still can identity the fact that beta and altitude appear to be the driving factors associated with velocity degradation. Additionally, had we selected a different response function that normalizes to initial velocity, some of the confounding may have been alleviated. We can conclude that low density materials proved to be unsatisfactory candidates for subbody type munitions because of the large amount of energy lost through aerodynamic drag.

4.3 Taguchi Analyses on Requirements

This final requirements section provides an overview of a number of high level system design parameters. Again, Taguchi techniques were employed to assess factor sensitivities. The analysis used the L54 orthogonal matrix to define parametric settings for each of the 54 experiments that were run. Figure 24 is the result of those calculations.

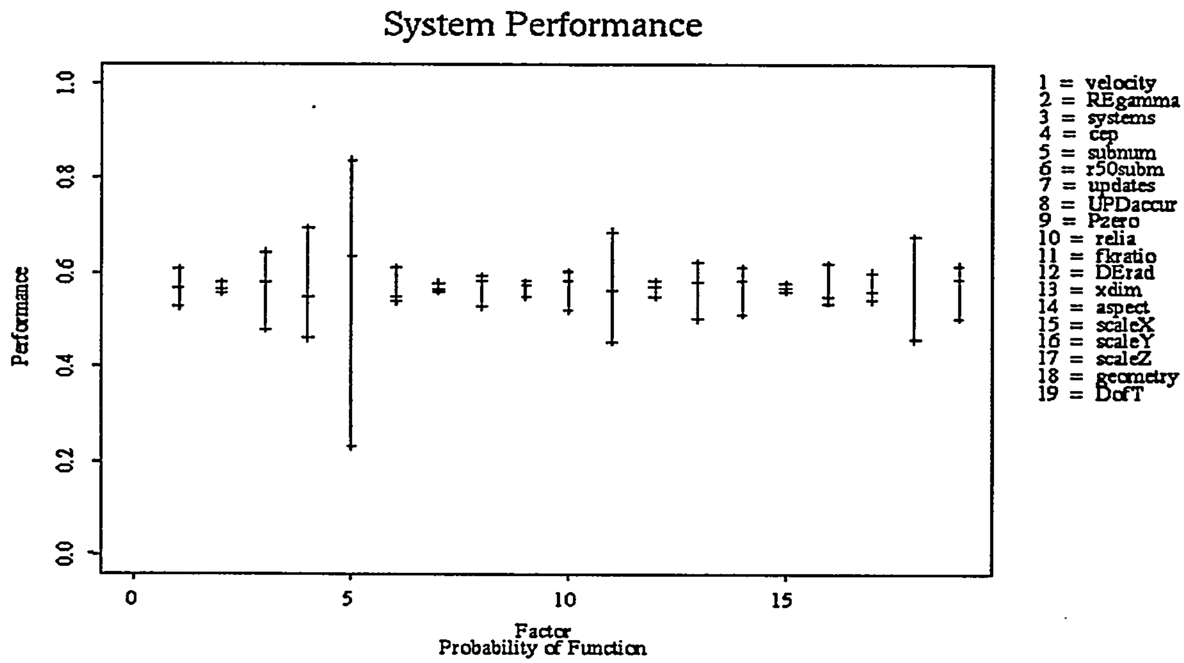

FIGURE 24. System performance sensitivities for a conventional KEW weapon.

The figure provides indications of the importance of the various parameters associated with a conventional KEW weapon system. The factors being examined are at a very high level of functionality. As a design effort progresses, more detailed analyses must ensue until a physics analysis transition can occur. The factors examined are included in Table 7.

Most factors are self explanatory; P_{zero} represents the initial accuracy of delivery, and fk_{ratio} is the fraction of the target profile that conceals the true functional target, xdim and aspect are target dimension and orientation parameters, and DofT is the target depth. The three scale parameters represent a quick look at the possibility of benefit to performance of preferential position corrections.

TABLE 7. System level factors used in the analysis.

Factor	Level 1	Level 2	Level 3
Velocity	8 kft/s	15 kft/s	22 kft/s
REgamma	35 deg	60 deg	85 deg
systems	1	2	3
CEP	20 ft.	40 ft.	60 ft.
subnum	1	10	20
r50subm	5	10	15
updates	0	1	2
UPD_{accur}	1 ft.	5 ft.	10 ft.
P_{zero}	5 ft.	10 ft.	15 ft.
reliability	0.9	0.95	1.0
fk_{ratio}	0.2	0.6	1.0
DE_{rad}	1 ft.	2 ft.	5 ft.
xdim	10 ft.	20 ft.	30 ft.
aspect	1.0	3.0	0.333
scaleX	0.7	0.85	1.0
scaleY	0.7	0.85	1.0
scaleZ	0.7	0.85	1.0
geometry	rectangular	elliptical	
DofT	5 ft.	10 ft.	15 ft.

The indications are that, from a system perspective and the factors and design levels selected, the important parameters affecting system performance are related to the numbers of systems and overall system accuracy. The second group of factors of near equal importance is related to operations and intelligence issues. When Taguchi techniques are employed, there is always the issue of confounding to consider in the factor analyses. A second set of calculations were run in which 6 factors were set to level-1 values, and the remaining factors were reassigned to different columns of the orthogonal matrix to uncover confounding effects. The results of these calculations are presented in Figure 25 .

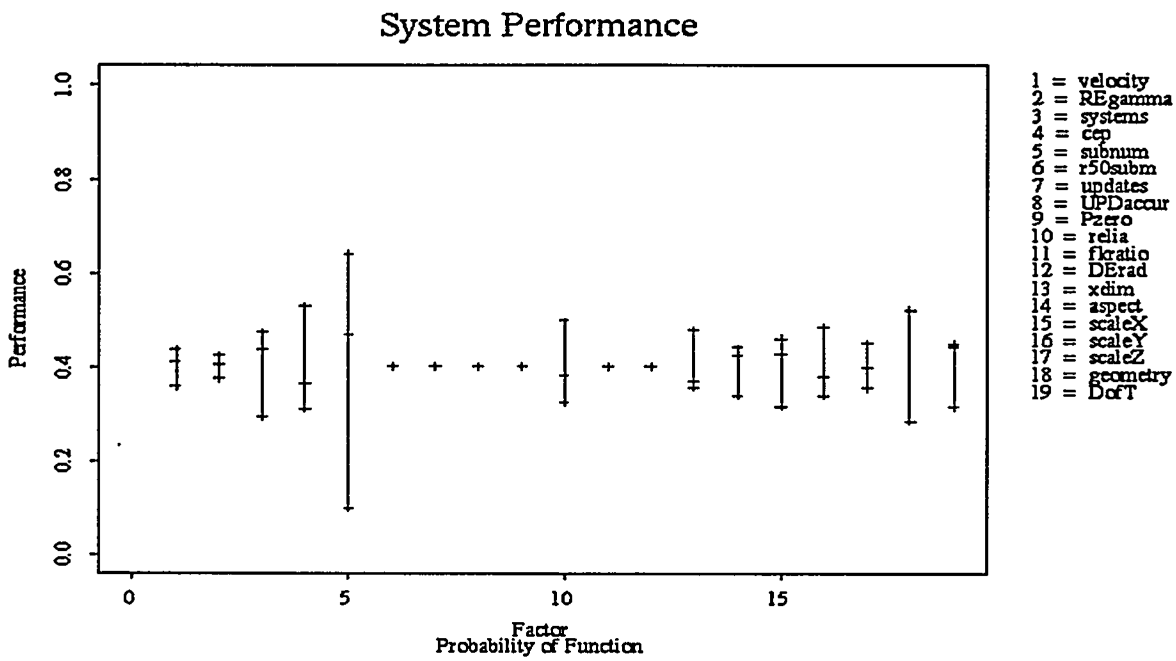

FIGURE 25. System performance with reduced number of factors considered.

This figure indicates the relative importance of the remaining factors to be consistent with the results shown in the previous figure. This provides the analyst with some level of confidence that the true characteristics of the system are emerging. The results indicate that a higher level of activity needs to be pursued which includes input and modification to the intelligence aspects and the operational elements of the mission problem. This system design activity must be tightly coupled to the user community in order to develop credible concepts.

4.4 Design Space of Kinetic Energy Concepts

It is important to recognize the kinetic energy weapon design space and the constraints which have lead to the current design subspace. The importance of this process is to ensure that the Navy is getting the best possible design for its money.

The obvious primary constraint that we must consider is the maximum velocity which a ballistic reentry body may possess. This velocity is based on the escape velocity for missiles leaving the earth, which is 36,700 ft/s. This is based on Equation 4.

$$V_{Escape} = \sqrt{(2 \cdot \mu)/r} \quad \text{(EQ 4)}$$

μ = 1.407654 x 1016 ft3/s2, while r is the radius of the earth.

The design envelope must now be pared down to reflect materials constraints, electronic and environmental sensor survivability constraints, and explosive material constraints. From these constraints, decisions can be made which lead to the optimum weapon system concept.

5.0 Concept Analysis

The last sections used the information developed in the functional analysis and requirements assessments to develop concepts for KE weapons. The concepts examined consist of systems: (1) using pre-reentry guidance and maneuver subsystems, (2) terminal guidance and maneuver, (3) dispersed submunitions, (4) pyrophoric subsystems, and conventional detonate-able warheads. The section immediately following examines the use of Taguchi techniques in a concept evaluation/trade-off study. The concept analysis builds on the preliminary analyses that were conducted as part of the sensitivity analyses. Operational analysis provides guidance on the identification of noise factors and design factors; differing operational scenarios could result in different sets of noise and design factors.

The operational scenario used in the following analysis assumes that there exists a moderate level of military target intelligence. The implication is that the targeteer can identify gross target structure and knows the function of the construction. The intelligence that is lacking is the exact layout of the internal structure. A facility may be identified as a rocket fabrication plant, but the location of motor storage can only be approximated based upon expert opinion. As a result, the functional kill ratio, fk_{ratio}, used in the past analyses must be considered a noise factor in the ensuing analyses. If the intelligence community could provide information on the actual production layout, it would become possible to use a fk_{ratio} that approaches a value of 1.0 and exhibits a much smaller variation.

Each of the concepts possess a number of similarities which reflect the constraints imposed on the design space. Each concept assumes a SLBM delivery system which can accommodate multiple warheads. There were a number of constraints violated in order to assess the likelihood of a viable concept which would require a level of fundamental research prior to development. In particular the spectrum of velocities exceed thermo-mechanical structural capabilities. The remaining characteristics are delineated in the next sections with the results of the Taguchi trade study presented in section 5.5.

5.1 Pre-reentry Guidance and Maneuver

The first concept assumed a highly accurate measurement and position modification capability prior to reentry. Upon reentry the body was assumed to be a pure ballistic body. The system is delivered to a reentry point with a high degree of accuracy which can be assessed to an accuracy of 5 ft. After position measurement, 70% of the position errors can be removed. This concept also employed a single large penetrator in an effort to disable/destroy the intended target. The design parameters are delineated in Table 8.

TABLE 8. High accuracy ballistic Concept.

Design Parameter	Value
Delivery system Cep (ft)	20
Number of sub-munitions	NA
Dispersion Cep (ft)	NA
Number of reentry updates	NA
Update accuracy (ft)	NA
Reentry measurement accuracy (ft)	5
System reliability	0.975
Position correction scale factors	0.75
Penetrator radius (cm)	10
Penetrator aspect ratio (L/D)	10

5.2 Terminal Guidance and Maneuver

The second system concept assumes that the system delivery requirements are reduced, but a capability exists to measure and correct for position errors prior to target impact (Table 9).

TABLE 9. High accuracy terminal concept.

Design Parameter	Value
Delivery system Cep (ft.)	40
Number of sub-munitions	NA
Dispersion Cep (ft.)	NA
Number of reentry updates	2
Update accuracy (ft.)	5
Reentry measurement accuracy (ft.)	10
System reliability	0.95
Position correction scale factors	1.0
Penetrator radius (cm)	10
Penetrator aspect ratio (L/D)	10

The concept is similar to the previous concept in all other aspects.

5.3 Dispersed Submunitions

This concept is different from the previous two concepts since it looks at the impact of a system that will disperse submunitions just prior to impact. The objective is to provide a mechanism that can compensate for the lack of perfect intelligence data. The load limitations on the delivery system makes it an impractical concept for achieving deep penetrations of buried targets. It does become a viable concept for use against surface structures housing fabrication facilities and hardened aircraft hangers. Under these conditions the target is lightly armored, and the precision location of the ultimate target is known with only a limited degree of accuracy. The concpt definition appears in Table 10.

TABLE 10. Submunition concept.

Design Parameter	Value
Delivery system Cep (ft.)	20
Number of sub-munitions	20
Dispersion Cep (ft.)	10
Number of reentry updates	NA
Update accuracy (ft.)	NA
Reentry measurement accuracy (ft.)	5
System reliability	0.975
Position correction scale factors	0.75
Penetrator radius (cm)	2
Penetrator aspect ratio (L/D)	5

5.4 Pyrophoric (JL^2) and Detonate-able Munitions

A final concept involves a set of calculations and sets of heuristics. A detailed assessment was not within the scope of these initial calculations. In this case, we are attempting to maximize the penetration of the target with projectiles that are either pyrophoric or a high density explosive. This concept relies on secondary effects for the damage mechanism. A pyrophoric into an ammunition storage or fuel storage facility is intended to begin a chain reaction of secondary explosions or fires. The idea is to maximize the potential of target hit, and once hit, maximize the probability of ignition. To complete the analysis on these types of concepts, additional lethality calculations need to be performed to enable us to generate fragility curves which reflect this type of phenomena.

The last issue to be considered to complete this study is determining the energy density needed for a high explosive to achieve acceptable levels of damage assuming the target could be penetrated. Explosive materials are being developed that have higher energy densities than traditional mixtures, and the follow-on analysis could provide research objectives for the physicists involved in this type of work.

The last concept examined looks at achieving the highest hit and penetration probability for use as the primary delivery mechanism for a different set of warhead paradigms. The conceptualized design parameters are delineated in Table 11.

The pyrophoric/ballotechnic technologies proved to be less effective than initially thought. The pyrophoric materials considered to possess the proper densities were not ignitable by aerodynamic heating but would have impact ignited under high velocity conditions. There does appear to be a possibility of coating the pyrophoric munitions with thermite to enable an aerodynamic ignition. This might provide an effective concept for use against storage and production facilities.

TABLE 11. High probability delivery concept.

Design Parameter	Value
Delivery system Cep (ft)	30
Number of sub-munitions	30
Dispersion Cep (ft)	20
Number of reentry updates	2
Update accuracy (ft)	5
Reentry measurement accuracy (ft)	10
System reliability	0.95
Position correction scale factors	0.9
Penetrator radius (cm)	2
Penetrator aspect ratio (L/D)	5

TABLE 11. High probability delivery concept.

5.5 Taguchi Analysis on Concepts

The analysis used in the concept studies assumes a moderate level of intelligence and the noise factor set consists of the following six variables from Table 7; $fk._{ratio}$, xdim, aspect, DofT, geometry, and DE_{rad}. This reflects uncertainties in intelligence, mission, and attack geometry, and to a small degree, the actual kill mechanism. The noise will be approximated by using the L_8 orthogonal matrix, which is a 2 level design. The concept analysis was achieved using the l_{16} orthogonal matrix in which the factors consisted of concept, attack velocity, reentry angle, the number of weapons in the attack, and either a steel protected target or a concrete bunker. This ordering permits us to evaluate a concept over a spectrum of operational conditions. The results are provided in Figure 26.

There are two basic missions and two system concepts tailored specifically for these missions. The first mission is a buried bunker in which a single large penetrator is used in the reentry warhead; and the second examines the potential of attacking an armored target with a dispersed submunition system.

The dominant factors in this analysis are the system concept and the mission. Over the spectrum of factors, the mission attack profile does not strongly affect system performance. This view may change somewhat if the analysis, examined the missions independently. Without the benefit of additional analysis we might conclude a fairly robust set of weapon system concepts. It also points out that the buried target mission may not be a reasonable mission for a ballistically delivered kinetic energy system. Under the spectrum of conditions, a 10-20% probability of kill does not seem to be useful. On the other hand, a system targeted for surface storage, production, defense against armored attacks, and counter mine activities there may be utility.

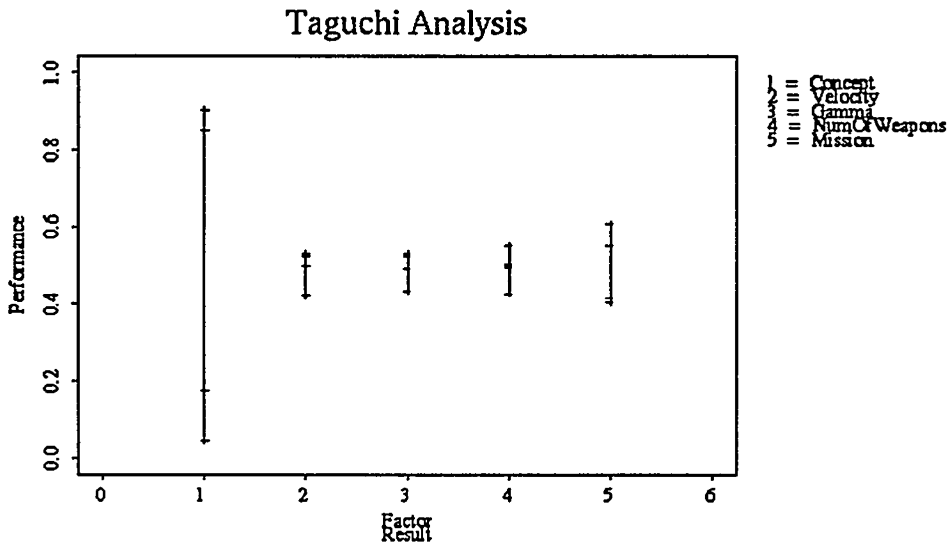

FIGURE 26. Results of the Taguchi concept analysis.

6.0 Study Summary

The purpose of this study was to develop a methodology that would help identify what constitutes a good concept. In order to achieve this objective traditional mission effectiveness metrics had to be reassessed for use in this conventional weapons arena. The reassessment (1) identified a process based on systems engineering principles appropriate for this study, (2) examined relevant physical principles developing the required data, (3) performed a rudimentary mission analysis, (4) examined a broad spectrum of generic target vulnerabilities, (5) performed a low level requirements analysis, (6) performed a set of trade studies based on Taguchi techniques, and (7) touched on follow-on activities appropriate for a study of expanded scope.

The basic tools applied in this study employed elements of mission analysis, functional analysis, requirements analysis and a form of trade study that took advantage of techniques developed by Taguchi. The objective functions or measures of effectiveness (MOE) took advantage of the expansive repository of work in the operations analysis fields. The MOEs defined in this study permit design engineers to examine a broad spectrum of concepts and provide a foundation for extending the design space beyond that considered in this small study.

Providing a robust analytical foundation resulted in the incorporation of techniques from a broad spectrum of engineering disciplines. The fragility curves used in the lethality estimations are extensively used in the fields of safety. While other techniques can provide lethality information for targets, they lack the flexibility for stochastic analyses or broad trade studies, both of which are essential in a well-executed systems engineering effort. Taguchi techniques are used in many areas of product and process design, especially in Japan. This methodology also lends itself to a stochastic treatment of design as opposed to the more traditional and limiting deterministic treatments.

The analytical framework employed a number of artificial life (A-life) analytical techniques to facilitate the more comprehensive set of calculations. Neural nets were used in a predictive role to provide fast efficient algorithms for use in assessing various system trades. The use of genetic algorithms was not used in this study, since a footprinting metric was not included in the decision variable set; however the efficiency and effectiveness of this technique have been demonstrated in earlier warhead studies.

A number of concepts were examined some of which proved to be ineffective early in the lethality analysis activities. The pyrophoric and ballotechnic concepts fell into this category. It also became evident that conventional and a number of nonconventional detonateable systems also fell out early in the lethality analyses. The final concept trade studies did not identify a conventional strategic concept that could provide the defense community with a highly cost-effective weapon system. In this case, cost effective implies the cost of the total weapon system versus the cost of targets destroyed. There does appear to be a potential for the concept. The requirements for that type of concept must be defined in some follow-on analyses. The objective of these analyses would be to provide research goals in a number of high technology areas.

6.1 Follow-on Studies

This study addressed a number of first order effects which need to be considered in conventional strategic systems. Follow-on studies should be considered to assess secondary weapon effects as well as a greater number of the inherent nonlinearities associated with a weapon. This could potentially broaden the design space for use by weapon systems designers in their search for viable conventional strategic systems. These nonlinear and secondary effects are areas that we as nuclear weapons designers traditionally neglect since the magnitude of a nuclear weapon effect can be used to mitigate uncertainties associated with a weponeering problem.

Another area of analysis is an examination of the energy content requirements of an explosive material for use in conventional strategic weapons systems. This study did not examine conventional explosive weapons in any great detail, but the additional analyses could provide objectives for materials research activities. The energy content of a hydrogen mixture by weight is about an order of magnitude greater than a high explosive. The problem with this material is being able to transport and disperse enough hydrogen to achieve the desired effect. Another example might be the use of a fullerene additive or replacement material in explosive materials. It is estimated that the use of fullerenes in the matrix of rocket fuels can significantly increase the specific impulse.

A broader mission analysis might be undertaken to examine additional nonconventional applications of strategic force. Conventional systems might be used in long range covering fire, providing ground forces with prompt air support. Examinations of submunition density patterns might reveal a mine clearing role for conventional systems in land and sea operations. The key to any future study is the mission analysis aspect of the problem.

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Appendix A. D.L. Potter Memo assessing thermal effects on sub-munitions.

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Albuquerque, New Mexico 87185

date: July 8, 1993

to: M. E. Senglaub, 5151

D. L. Potter

from: D. L. Potter, 1553

subject: Parametric Thermal Analysis of Magnesium & Uranium Spheres as Entry Bodies & Spherical Drag Model Addition to HANDI

Abstract

High velocity magnesium and uranium spherical bodies released at low altitudes were evaluated for possible conventional warhead applications. Equilibrium thermochemical, convective heating, and material thermal response analyses were completed. Predicted surface effects (i.e. melting, burning, etc.) were nonexistent for release altitudes up to 2000 *ft* at velocities reaching 16,000 *ft/sec*. Sphere diameters of 1 and 6 *inches* were examined. Code development completed during the analysis, included addition of a user friendly subroutine to the department's analysis capabilities for predicting the spherical drag coefficient.

Introduction

A series of calculations were made for spherical bodies released at low altitude for possible conventional warhead applications. Magnesium and uranium spheres were examined for diameters of 1 and 6 *inches*. Release altitudes ranged from 100 to 2000 *ft* for initial velocities up to 16,000 *ft/sec*. Equilibrium thermochemical, convective heating, and material thermal response analyses were performed. In addition, thermochemical/mechanical response of the magnesium surface is discussed along with a spherical drag model added to the HANDI code.

Parametric Definition

Five parameters were varied to give different flight paths following release of the spherical bodies. They were velocity, altitude, perpendicular velocity delta, sphere diameter, and material. Tables 1 and 2 summarize the parametric conditions for the magnesium and uranium spheres respectively. All magnesium calculations were made for 1 *inch* diameter

Table 1: Magnesium Sphere Release Variables

Diameter (*in*)	Altitude (*ft*)	Delta Velocity (*ft/sec*)	Velocity (*ft/sec*)
1	100	50	8000
1	100	50	12,000
1	100	50	16,000
1	550	250	12,000
1	2000	100	16,000

spheres, whereas uranium evaluations examined both 1 and 6 *inch* diameters. Release al-

Table 2: Uranium Sphere Release Variables

Diameter (*in*)	Altitude (*ft*)	Delta Velocity (*ft/sec*)	Velocity (*ft/sec*)
1	100	250	16,000
1	550	100	8000
1	550	100	12,000
1	550	100	16,000
1	2000	50	12,000
6	100	100	12,000
6	550	50	16,000
6	2000	250	8000
6	2000	250	12,000
6	2000	250	16,000

titudes for both materials were varied from 100 to 2000 *ft*. Additionally, velocities ranged from 8000 to 16,000 *ft/sec* for magnesium and uranium. Finally, perpendicular velocity deltas were varied from 50 to 250 *ft/sec* for all configurations. With these release conditions, flight durations following release are very short ranging from approximately 0.008 to 0.30 *seconds*.

<u>HANDI Spherical Drag Model</u>

To assist in parametric trajectory definition for the range of conditions encountered at release, a user friendly spherical drag coefficient model was incorporated into **HANDI**[1]. The drag model subroutine (SPHDRAG) makes use of the correlation work done by Kuntz and Amatucci[2] on the ballistic range data of Bailey and Hiatt[3]. This data was obtained at the Von Karman Gas Dynamics Facility at the Arnold Engineering Development Center. Laminar drag data was correlated for Mach numbers ranging from 0.1 to approximately 6, with Reynolds numbers based on diameter varying from 5 to 100,000. In addition, the model was extended in **HANDI** using information from Hoerner[4] showing the drag coefficient becoming essentially constant above Mach numbers of 10 with a value of 0.92. Linear interpolation on Mach number between end points of 6 and 10 was used to smoothly blend the two models.

<u>Magnesium Thermochemistry & Surface Behavior</u>

Magnesium surface thermochemistry ablating in air was modeled using the Aerotherm Chemical Equilibrium (ACE) program[5]. Since magnesium is a melting material, the thermochemistry modelling approach was similar to that for the silica in a silica-phenolic deck. Previous discussions with Aerotherm labelled this the "total deck" approach. As such, a fail temperature is chosen sufficiently above the melt temperature of the material being modelled to allow the material to soften to the point of flowing. For silica, this has been modelled in the past as 45% of the way between melt and vaporization temperature. With magnesium melt and vaporization temperatures of 1660 and 2480^{o}R respectively, a failure temperature of 2025^{o}R (1125 *K*) was chosen. The resulting enthalpy characteristics of the magnesium/air mixture are shown in Figure 1. It is evident from the illustration where surface specie failure occurs by the vertical rise in enthalpy at 2025^{o}R. These points continue

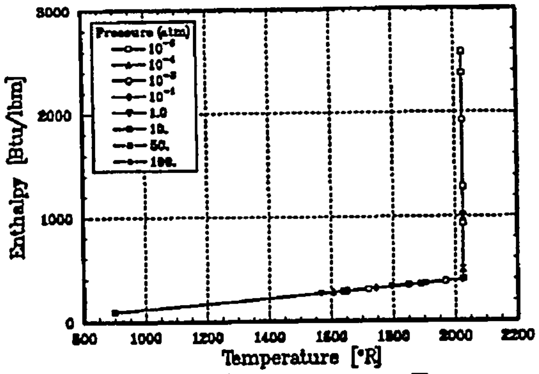

Figure 1 - Magnesium/Air Enthalpy vs Temperature

to higher enthalpies due to increasing surface material char rates. The enthalpy tables generated by ACE are used in subsequent thermal response calculations. Tabulated enthalpy values represent wall enthalpy in the surface energy balance calculations.

Magnesium surface behavior during reentry heating has been the subject of considerable speculation. Following is the evaluation of the surface behavior characteristics by I. Auerbach[6] based on his understanding of the fundamental chemistry.

> *"Pure magnesium will have a loosely sealed coating of magnesium oxide at room temperature. When propelled, the coating will be removed by the shear forces and a new coating will be regenerated. Melting will occur at 1660°R. However, the tensile strength will drop to very low values appreciably below its melt temperature. The sphere may break up, therefore, before melt.*
>
> *As a liquid, the surface will be changing more rapidly and mass loss should be greater than that for a solid because of renewed surface area. Whether the liquid breaks up will depend on the forces it experiences and the surface tension of liquid magnesium. Depending on these numbers, a limiting size droplet may result. No burning is expected, since liquid magnesium is conventionally handled by fabricators when poured into various molds.*
>
> *As the temperature rises toward the boiling point, the vapor pressure will increase and the ensuing vapor will probably burn. All of these phenomenon are time dependent. Considering the very short flight duration, some or many of the above phenomenon may not occur."*

Heating

Surface heating was predicted for all cases using the **HANDI** code **CONVECTIVE** subroutine assuming a random tumble and spin entry orientation. Data analysis results are divided into **magnesium** and **uranium** sections.

Magnesium:

Convective heating results for the 1 *inch* diameter magnesium spheres are illustrated in Figures 2 and 3. Figure 2 contains the heating history for spheres released at an altitude of

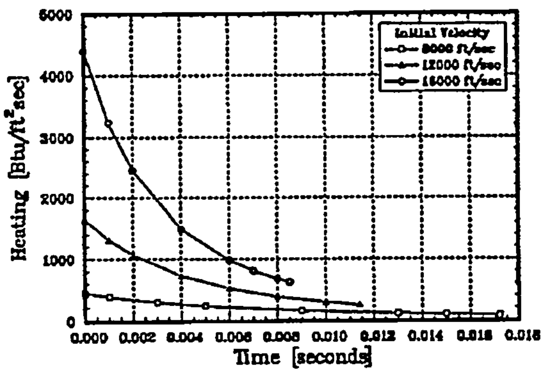

Figure 2 - Magnesium Sphere Heating (A_0=100 *ft*)

100 *ft*. Release velocities ranged from 8000 to 16,000 *ft/sec*. Maximum flux is approximately 4400 *Btu/ft²sec* for the release velocity of 16,000 *ft/sec*. Figure 3 compares the two

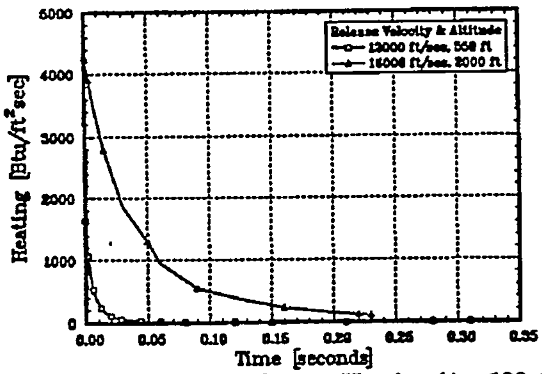

Figure 3 - Magnesium Sphere Heating (A_0>100 *ft*)

cases released at altitudes of 550 and 2000 *ft*. Maximum heating for this pair of points occurs for the case released at an altitude of 2000 *ft* with a velocity of 16,000 *ft/sec*. Its is reduced fractionallyfrom the previous comparison to approximately 4300 *Btu/ft²sec*, due to the slightly higher altitude. However, integrated heating is larger due to a much greater flight time (0.23 vs 0.0083 *sec*). Heating drops off with time for all cases due to velocity reduction from drag.

Uranium:

Uranium spheres with 1 and 6 *inch* diameters were evaluated. Random tumble and spin spherical heating histories for the 1 *inch* diameter geometry are shown in Figures 4 and 5.

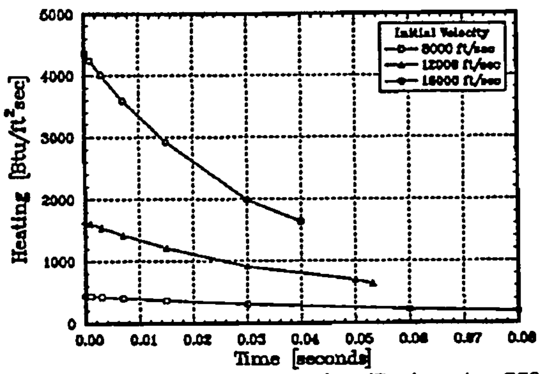

Figure 4 - Uranium Sphere Heating (D=1 *in*, A_0=550 *ft*)

Cases compared in Figure 4 are for a release altitude of 550 *ft*. Release velocities were again varied from 8000 to 16,000 *ft/sec* (as in the magnesium evaluation). Maximum heating at release is similar to the magnesium evaluation (i.e. approximately 4400 *Btu/ft²sec*). Flight times ranged from 0.04 to 0.08 *sec*. Figure 5 compares the points released at altitudes of 100 and 2000 *ft*. Maximum heating is again approximately 4400 *Btu/ft²sec* for the case released at 16,000 *ft/sec* velocity. The second point had a release velocity of 12,000 *ft/sec* at an altitude of 2000 *ft* and experienced release heating of approximately 1700 *Btu/ft²sec*. This is typical of all random tumble and spin average heating values for 1 *inch* diameter spheres released at low altitude at this velocity.

Results for the 6 *inch* diameter spheres are compared in Figures 6 and 7. Initially, calculations were made for release altitudes of 2000 *ft*. Figure 6 illustrates these points for re-

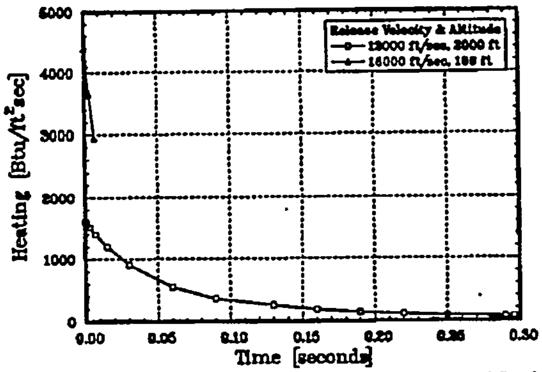

Figure 5 - Uranium Sphere Heating (D=1 *in*, A_0 Varied)

lease velocities ranging from 8000 to 16,000 *ft/sec*. Peak heating is considerably reduced relative to the 1 *inch* diameter spheres since heating is inversely proportional to the square root of the diameter. Maximum heating for the 16,000 *ft/sec* release velocity is approxi-

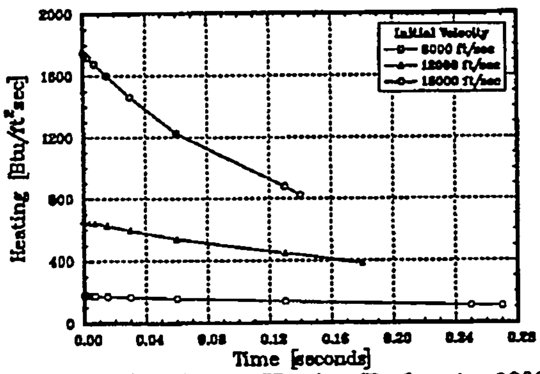

Figure 6 - Uranium Sphere Heating (D=6 *in*, A_0=2000 ft)

mately 1750 *Btu/ft²sec*. Figure 7 compares the results for release altitudes of 100 and 550 *ft*. Release velocities for these two points are 12,000 and 16,000 *ft/sec* respectively. Maximum

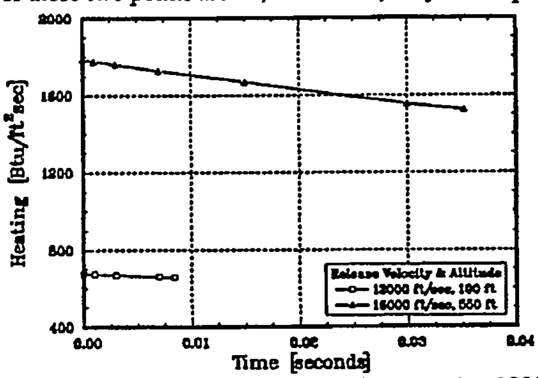

Figure 7 - Uranium Sphere Heating (D=6 *in*, A_0<2000 ft)

heating for the 16,000 *ft/sec* release condition is similar to the previous 2000 *ft* altitude release case (i.e. 1750 *Btu/ft²sec*). The initial heat flux for the 12,000 *ft/sec* release is approximately 675 *Btu/ft²sec.*

Thermal Response

The Charring Materials Ablation (CMA) code[7] was used to calculate the magnesium and uranium sphere thermal response. CMA is a one-dimensional, implicit, finite difference, transient heat conduction code which allows for ablation at one surface and in-depth material decomposition. It requires complex thermochemical enthalpy information as input to perform the surface energy balance (including radiative cooling) when surface heating is applied. The ACE code, previously discussed, provides the necessary boundary layer enthalpy information in tabular form as a function of temperature, char rate, and parametric in pressure. ACE was ran for magnesium ablating in air to generate the input tables representing wall enthalpy in the surface energy balance (i.e. the total decks). Assigned char rate and pressure chemical equilibrium calculations were performed for an ablating open system assuming unequal diffusion coefficients. Uranium was treated in a different fashion than magnesium employing the q^* approach. The nonablating surface option was used in ACE to calculate air wall enthalpy thermochemistry since q^* CMA calculations were made for the uranium spheres. An ablating surface modelled by q^* implies a fixed energy consumption rate per unit surface mass. Ablation temperature and a constant value for q^* are inputs to CMA. Thermal response analysis summaries are presented in magnesium and uranium sections.

Magnesium:

Thermal response results for the 1 *inch* diameter magnesium sphere calculations are shown in Figures 8 and 9. Figure 8 compares the response for spheres with a release alti-

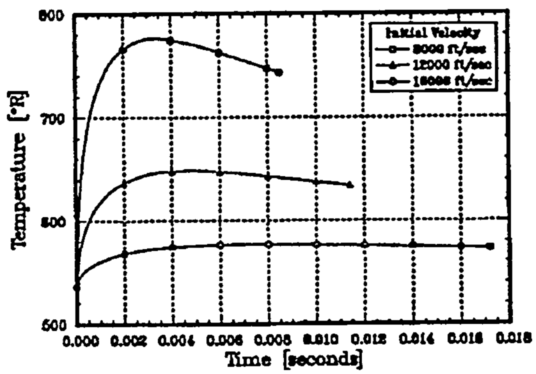

Figure 8 - Magnesium Sphere (D=1 *in*, A_0=100 ft)

tude of 100 *ft* with velocities from 8000 to 16,000 *ft/sec*. Surface temperature peaks for the maximum velocity case at approximately 775°*R* and begins to decline limited by velocity/heating drop off resulting from drag. This temperature is well below the melt and vaporization temperatures of magnesium (i.e. 1660 & 2480°*R* respectively). No burning would be expected on the surface of the sphere. Temperature histories for the spheres released at 550 and 2000 *ft* are shown in Figure 9. Temperature response for the 16,000 *ft/sec* release velocity (A_0=2000 ft) is considerably greater than before due to the more sustained heating profile (compare Figures 1 & 2). Higher integrated heating produces a surface temperature peak in this instance at approximately 1175°*R*. The resulting peak temperature is still approximately 500°*R* below the 1660°*R* melt temperature of magnesium. As before, the burning of magnesium is speculative and not likely to occur on the surface of the sphere. Examination of the in-depth temperature profile illustrates another mechanism limiting the

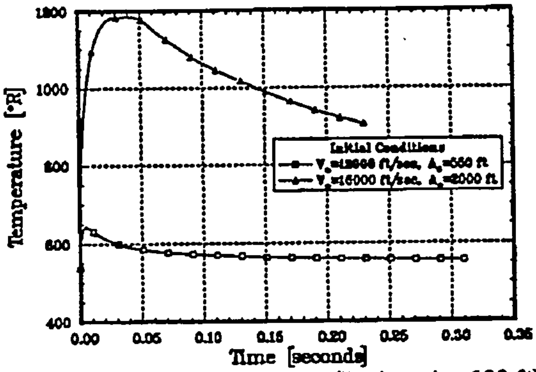

Figure 9 - Magnesium Sphere (D=1 *in*, A_0>100 ft)

magnesium surface temperature for the longer flight duration release points (i.e. t > 0.1 *sec*). Magnesium has relatively high thermal conductivity and allows for considerable energy

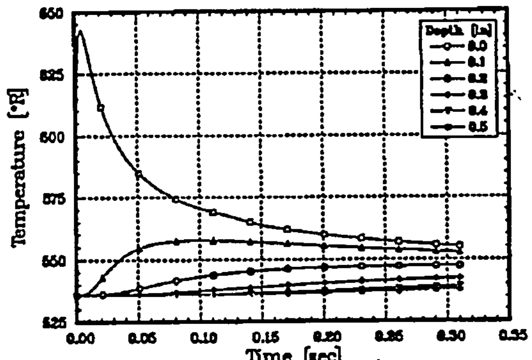

Figure 10 - Magnesium Sphere (D=1 *in*, A_0=550 ft)

deposition in-depth (see Figure 10).

Uranium:

Results for the 1 *inch* uranium spheres are summarized in Figures 11 and 12, Surface temperatures for the points with a release altitude of 550 *ft* are grouped in Figure 11 with release

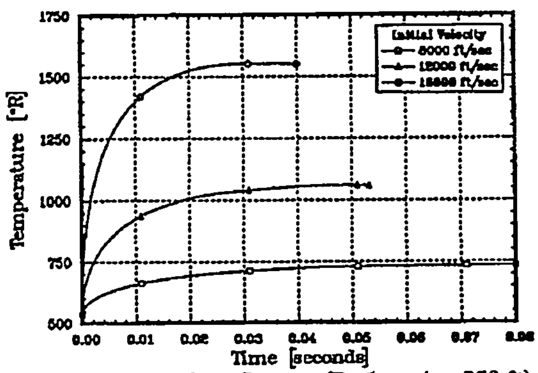

Figure 11 - Uranium Sphere (D=1 *in*, A_0=550 ft)

velocities once again covering the 8000 to 16,000 *ft/sec* range. Temperature increases much more rapidly for the uranium vs magnesium spheres with comparable diameter and release velocities since thermal conductivity is a factor of two less. In addition, uranium is much more dense giving it a higher baslistic coefficient; thus maintaining higher velocity and heating rates during flight. The 16,000 *ft/sec* case reaches approximately $1550^{o}R$ at impact. As with the magnesium, this is well below the materials melt temperature (i.e. $2529^{o}R$). No surface ablation/melting/burning is anticipated. Figure 12 contains the surface thermal re-

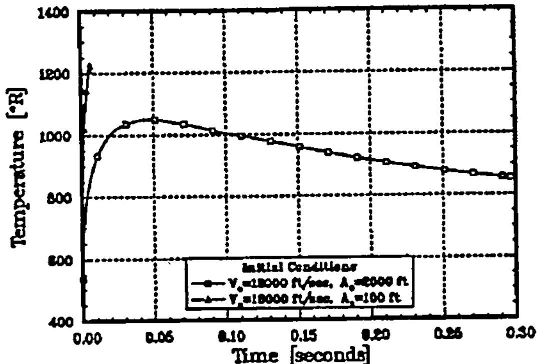

Figure 12 - Uranium Sphere (D=1 *in*, A_0 Varied)

sponse information for 1 *inch* diameter spheres with release altitudes of 2000 and 100 *ft*. Release velocities were 12,000 and 16,000 *ft/sec* respectively. The higher velocity point reached $1225^{o}R$ prior to impact from its 100 ft release altitude. Similar to the previous 12,000 *ft/sec* release point, uranium surface temperature peaked at approximately $1050^{o}R$. No surface degradation is anticipated for any 1 *inch* diameter sphere.

The 6 *inch* diameter sphere thermal results are shown in Figures 13 and 14. Figure 13 illustrates the results for cases with a 2000 *ft* release altitude. Surface temperatures at im-

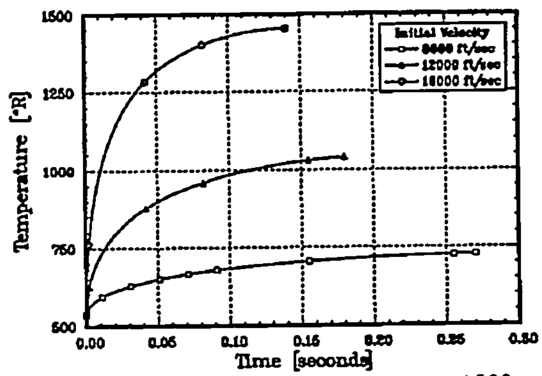

Figure 13 - Uranium Sphere (D=6 *in*, A_0=2000 *ft*)

pact are similar to the same velocity parametric comparison shown for the 1 *inch* diameter in Figure 11. However, temperature rise rate is slower for the 6 *inch* diameter sphere due to its reduced heating rates. The increased flight time offsets this difference. Further examination of the 6 *inch* diameter geometry is illustrated in Figure 14. Response to release velocities of 12,000 and 16,000 *ft/sec* at altitudes of 100 and 550 *ft* respectively was evaluated. Impact times were down proportionally with release altitude for a given initial velocity. Surface temperature rises to approximately $1300^{o}R$ at impact for the maximum release velocity evaluation (i.e. 16,000 *ft/sec*). The surface temperature of the sphere released at an altitude 100 *ft* reaches $725^{o}R$ prior to impact due to a very short flight time ($t < 0.01$ *sec*).

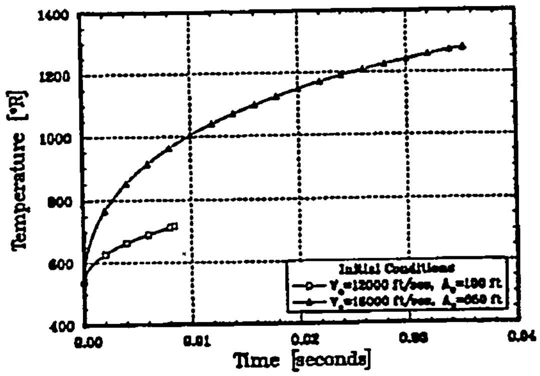

Figure 14 - Uranium Sphere (D=6 *in*, A_0 Varied)

As for the 1 *inch* sphere, no surface effects (i.e. ablation, melting, etc.) are anticipated for the 6 *inch* diameter uranium spheres regardless of the examined parametric condition.

Conclusions

Surface ablation or melting is not predicted for the magnesium or uranium spheres under the specified release conditions. In addition, ignition of the magnesium is not anticipated to the best of our understanding. Higher ballistic coefficient configurations are needed to maintain velocity and heating rates to drive surface temperatures up to increase degradation effects. Ignition at impact is an effect which should be further investigated.

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