

**Encapsulation of Large Scale Policy Assisting
Computer Models**

by

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(ABSTRACT)

In the past two decades policy assisting computer models have made a tremendous impact in the analysis of national security issues and the analysis of problems in various government affairs. SURMAN (Survivability Management) is a policy assisting model that has been developed for use in national security planning. It is a large scale model formulated using the system dynamics approach of treating a problem in its entirety rather than in parts.

In this thesis an encapsulation of SURMAN is attempted so as to sharpen and focus its ability to perform policy/design evaluation. It is also aimed to make SURMAN more accessible to potential users and to provide a simple tool to the decision makers without having to resort to the main frame computers. To achieve these objectives a personal/micro computer version of SURMAN (PC SURMAN) and a series of curves relating inputs to outputs are developed.

PC SURMAN reduces the complexity of SURMAN by dealing with generic aircraft. It details the essential survivability management parameters and their causal relationships through the life-cycle of aircraft systems. The model strives to link the decision parameters (inputs) to

the measures of effectiveness (outputs). The principal decision variables identified are survivability, availability and inventory of the aircraft system. The measures of effectiveness identified are the Increase Payload Delivered to Target Per Loss (ITDPL), Cost Elasticity of Targets Destroyed Per Loss (CETDPL), Combat Value Ratio (COMVR), Kill to Loss Ratio (KLR), and Decreased Program Life-Cycle Cost (DPLCC).

The model provides an opportunity for trading off decision parameters. The trading off of survivability enhancement techniques and the defense budget allocation parameters for selecting those techniques/parameters with higher benefits and lower penalties are discussed. The information relating inputs to outputs for the tradeoff analysis is presented graphically using curves derived from experimentally designed computer runs.

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1.0 INTRODUCTION

1.1 ENGINEERING -- CIVIL AND MILITARY

Technology and public policy are interrelated phenomena. Beginning with ancient civilizations, nations have sought appropriate technologies to serve their military and civil, or social, needs. Civil engineering, once all of engineering except for military engineering, has been eroded over the past two hundred years with the creation of mechanical, electrical, chemical, mining, petroleum, aeronautical, industrial, ocean and coastal engineering. What remains is less a discipline than a coalition of leftovers -- structures, soils, hydraulics, materials, water resources, geodetics, urban engineering, sanitary engineering, sanitary engineering, environmental science, construction, city management and transportation. Depleted and fragmented as it is, civil engineering still presents the greatest breadth of understanding in coping with modern day problems. Nowhere is the breadth better illustrated than in transportation engineering.

Transportation, more than any discipline, erases the artificial barriers that have led to the distinction between civil and military. Throughout history such formidable transportation ventures as the Great Wall, the Apian way, the Suez Canal, the Trans-Siberian railroad, the Panama Canal, the U.S. Interstate Highway System, and the U.S. Space Program have fostered socio-economic development even though they were justified on military grounds. War -- both hot and cold -- is an important

institution of society and a fundamental tool of national policy. This basic truism has not escaped the market place. In the March 1985 issue of "Graduating Engineer" published by McGraw-Hill under "Job Prospects for Civil Engineers" on p102, we quote

An important job opportunity which should not be overlooked is military spending, especially regarding aircraft, vehicles and ships.

Indeed Aerospace is now a recognized division of the American Society of Civil Engineers.

The experience of past wars has made clear the vital role of transportation in the planning and conduct of military operations. The marshalling of a nation's war potential and its use against the enemy depends heavily on the capacity of its transportation system to effect the necessary movement of men and material. Transportation has inevitably been accorded high priority in considerations of defense because it is required for all of the following : (1) direct destruction of enemy infrastructure and military targets, fighter-attack aircraft, submarines and tanks (all transport vehicles), (2) direct military support using transport aircraft, ships and trucks, and (3) the maintenance of national economy so that resources can be made available for the conduct of war [1]. To varying extents, this thesis deals with all three, achieved through the application of a large-scale computer model.

1.2 MILITARY MODELING

War and games representing war predate recorded history. Game boards and symbolic representation of soldiers and military equipment have been

unearthed in archeological explorations in Greece, Egypt, Persia, China and India. Chesslike games, thought to have been games of war, were played by the ancient Indians, Iraqis, Chinese, Japanese, and others [2]. Since war is one of humanity's oldest activities, and one that involves great costs, it is not surprising that substitutes have always existed. With its outcome, either victory or defeat, come vast social and material changes. It is these that cause men to investigate methods by which the consequences of their actions may be predicted.

Such considerations provide the justification for an examination of the factors involved in combat, whether it be large or small. The approach used in this work will be mathematical. A battle is an extremely complex phenomenon involving many intangibles besides the generally recognized such as the effectiveness of weapons and force sizes. In most cases, a mathematical approach which has any hopes of being simple enough to be tractable must leave many lesser factors out of consideration. This may considerably reduce the effectiveness of the approach for the purposes of precise prediction. Its most significant role, however, seems to reside in its great potentiality for highlighting the relationships among key factors and determining how these are affected by changing the tactics employed. The importance of these relationships lies less in their use to commanders in the field than in aiding long range military planners to differentiate between many possible courses of action.

The use of gaming to study contemporary warfare has evolved rapidly in recent years. Particularly important strides were taken during the 1960's and 1970's with advances in computer technology and the development of broader ranges of subject matter. The past two decades have seen a

tremendous expansion in the role and influence of computer models as "policy assisting" device -- first in the analysis of national security issues, and now for the analysis of problems arising throughout the entire affairs of Government.

While the scope and stakes of military modeling have escalated over centuries, reduced to its basic elements, the most sophisticated computer representation of a conflict situation has the same key ingredients: two sides, a contest, rules and constraints, and a variety of scenarios that might be played out when the time comes to wage war in earnest.

1.3 COMBAT MODELING

Mathematical representations of combat have long fascinated analysts and practitioners. In 1805 at the Battle of Trafalgar, Nelson faced a combined French and Spanish force of 46 ships with his fleet of 40 ships. History records that he deployed 8 of his ships to hold half of the enemy fleet downwind while his main force of 32 ships engaged 23 ships in the rear. Over a hundred years later Lanchester tested his classical theory of combat which states that superiority is proportional to the squares of the respective numerical strengths [3]. According to Lanchester's model, Nelson faced a fighting strength of $23^2 + 23^2 = 1,058$. By dividing his force as he did, he met the enemy with a margin of superiority of $\sqrt{32^2 + 8^2} - 1,058 = 5.5$ ships. Eight ships was the most that could have been deployed and still have maintained this superiority. If less had been assigned, they might not have been able to have contained the 23 until his force of 32 had destroyed the enemy and come to their aid.

To begin understanding combat models, it is useful to review some basic concepts. Simply stated, all combat involves the interaction between two opposing forces, which can be designated as RED and BLUE, IVAN and SAM, or simply X and Y. The forces are composed of men and equipment, are governed by operating procedures, and involve some measure of combat support. Both forces function in an operational environment, which is composed of natural factors, such as weather and terrain. The interaction between IVAN and SAM both affects, and is affected by, factors such as :

- Command and Control (mission, composition of force, supporting units, battle plan, time of battle, and posture)
- Logistics (resupply, transportation, medical, maintenance facilities and construction)
- Attrition or Combat Losses including
 - weapon/target characteristics (air-to-air, air-to-ground, ground-to-air, and ground-to-ground)
 - munition characteristics (precision, guided or free-flight, fragmenting or solid shot, etc)
 - engagement characteristics (visibility, range, altitude, etc).

The interaction between Ivan and Sam results in a combat operations outcome, which is routinely measured in a variety of ways :

1. Movement of Forward Edge of Battle Area (FEBA)

2. Attrition (personnel and/or weapons including destruction and damage)
3. Resource consumption (ammo expended, fuel used, supplies consumed, and equipment cost).

Model outputs usually take the form of periodic status reports that give a time history of battle evolution. Iteration of the process over a specified number of days produces a time history of war. Such models might be used to, provide insight into questions concerning :

- systems choice such as between comparable weapon systems,
- systems mix such as between noncomparable weapon systems,
- force structure such as choices in organization or force mix
- force level -- that is, how much is enough ?

Combat models can be classified as to levels of disaggregation. Aggregated and detailed models embody fundamentally different representations of combat. Aggregated models may lump together similar types of weapons or assume that forces are concentrated at a point. In contrast, detailed models present a more definitive representation of combat. Obviously, the more detailed the model, the more explicit the modeller's judgement and greater the ability to modify critical parameters to reflect changes in tactics and battle doctrine. However, it is equally apparent that some aggregation is necessary in order to make the model manageable.

Battles are fought in both time and space. The modelling process, in addition to the spatial representation of forces, is basically one of breaking time into discrete intervals or periods. The initial conditions at the beginning of a period are used to predict what will happen during the period, and the predicted results become the initial conditions for the subsequent period. The usual tradeoff between aggregation and detail apply in the selection of the solution interval for a model.

1.4 CLASSICAL ATTRITION MODELS

The approach used to model attrition dominates all facets of a combat model. Not only does it determine winners and losers and the movement of the front-line, but also gives casualty levels, equipment losses, ammunition expenditures, and resupply/reinforcement requirements.

In order that a mathematical model may be developed in a concise manner, it is necessary that now we define the fundamental concepts.

A "force" is a body or collection of organized fighting units.

These "fighting units" may consist of men, ships, airplanes, tanks or any other component which is capable of contributing to the victory of its side. There are many factors which contribute to this capability. These could include weapon effectiveness, speed, maneuverability, vulnerability etc. A fighting unit is said to be destroyed when it is no longer capable of contributing to the success of its own side.

Two adversaries, Ivan and Sam, each deploying a force are engaged in a conflict, the conflict ending when one force breaks off the encounter.

The force which does not break off the conflict is said to have won the battle.

The properties of the fighting units may be summarized into two sets of constants, b and c , called "attrition coefficients". The manner in which this summarization is performed is dependent on the situation. Details will be delayed until specific models are considered.

The rate at which the size of a given force is diminished is called the "rate of attrition".

The formulation of a model for a particular situation depends on many factors. Among the most important of these are: i) types of units involved and weapons possessed, ii) tactics employed by each side.

Having then determined the interaction of one opponent on the other, one considers the type of mathematical analysis to be attempted, and its objectives.

The most famous approach to attrition modeling was introduced by Frederick W. Lanchester in World War I and attempted to describe the effects of concentration in warfare by means of differential equations. The sets have come to be known as Lanchester's linear law and Lanchester's square law. The former is a representation of combat where there is no concentration of force, but rather - area fire where shooters do not know when a target is killed. The latter is a representation of concentration -- aimed fire; that is shooters know when a target is killed, and concentrate their fire on the survivors.

Let S and X be the two opponents, S_0 and X_0 their respective strengths, and S_t and X_t the strengths at time t after the start of the conflict.

The rate of decrease in $\$t$ and Xt is governed by differential equations of the type

$$d\$t/dt = -b f(\$t, Xt) \quad (1.1)$$

$$dXt/dt = -c g(\$t, Xt) \quad (1.2)$$

In the case of the "Linear" law,

$$f(\$t, Xt) = \$t Xt \quad (1.3)$$

$$g(\$t, Xt) = \$t Xt \quad (1.4)$$

and if time is eliminated from (1.3) and (1.4) we obtain

$$d\$/dX = b/c \quad (1.5)$$

which gives, using initial conditions,

$$c\$ - c\$_0 = bX - bX_0 \quad (1.6)$$

Assuming that complete annihilation occurs for the side that loses, the battle will be complete and the number of units surviving will be positive for the victorious force and zero for the vanquished. It follows from (1.6) that if $c\$_0 > bX_0$, $\$$ is still positive when X vanishes so that $\$$ wins. Similarly X wins if $bX_0 > c\$_0$. A time dependent solution may be obtained by solving the simultaneous differential equations giving

$$\$t = \frac{(bX_0 - c\$_0)\$_0 e^{-(bX_0 - c\$_0)t}}{bX_0 - c\$_0 e^{-(bX_0 - c\$_0)t}} \quad (1.7)$$

and $X_t = X_0 - (c/b)\$_0 + (c/b)\$_t$, $bX_0 \neq c\$_0$ (1.8)

For the special case where $bX_0 = c\$_0$,

$$\$ _t = \$ _0 / (c\$ _0 t + 1) \tag{1.9}$$

The governing simultaneous differential equations for Lanchester's square law model are obtained by replacing equation (1.3) and (1.4) with

$$f(\$ _t, X_t) = X_t \tag{1.10}$$

$$g(\$ _t, X_t) = \$ _t \tag{1.11}$$

If time is eliminated, one obtains

$$d\$ / dX = bX / c\$ \tag{1.12}$$

Integrating this and applying initial conditions,

$$c\$ ^2 - c\$ _0 ^2 = bX ^2 - bX_0 ^2 \tag{1.13}$$

Once again, assuming that the battle continues until one side is annihilated, we find that the condition for \$ to win is $c\$ ^2 > bX^2$.

The time dependent solution is

$$\$ _t = \$ _0 \cosh \omega t - \sqrt{b/c} X_0 \sinh \omega t \tag{1.14}$$

$$X_t = \sqrt{X_0 ^2 - (c/b)(\$ _0 ^2 - \$ _t ^2)} \tag{1.15}$$

where $\omega = \sqrt{bc}$ (1.16)

1.5 AIRCRAFT COMBAT SURVIVABILITY

The U.S. lost 2561 fixed winged aircraft and 2587 helicopters in the Viet Nam War [4]. As a result of the attrition rates in Southeast Asia, the Joint Technical Coordinating Group on Aircraft Survivability (JTCCG/AS) was established in the 1970's. The JTCCG is chartered to coordinate the non-nuclear survivability research and development effort within the three services (the Army, the Navy, and the Air Force) of the Department of Defense.

Aircraft combat survivability is defined by the United States Department of Defence as "the capability of an aircraft to avoid or withstand a man-made hostile environment without sustaining an impairment of its ability to accomplish its designated mission" [5]. From this definition, the broad scope of the concept of survivability is evident leading the JTCCG to update its response to its charter requirements to include the promotion of survivability as a design discipline and the coordination of research and development results among the military services and industry, as well as within the services.

Indicative of the breadth and depth of the aircraft survivability discipline is the material assembled in a four volume military handbook entitled "Survivability, Aircraft, Nonnuclear" [6]. This Handbook was prepared to provide military planners and industry with the information and guidance needed for the conceptual and detailed design of new aircraft where nonnuclear survivability is to be integrated into the system. However, while the emphasis on detail in the Handbook, in particular, and

in the survivability community, in general, serve the design function very well, planning and management require a comprehensive "big picture".

1.6 STRATEGIC PERSPECTIVE SYSTEMS APPROACH

The past four decades have seen a vast array of developments in military technology and tactics. Often these new capabilities have been demonstrated only on a small scale in wars peripheral to the main streams of history without decisive results. While we have been aware of their individual occurrence, we have not fully comprehended how their convolution renders essentially obsolete many aspects of the fundamental military techniques that emerged from World War II. New tactics and technologies can preserve their usefulness only by challenging existing concepts and trends.

A description of the effect on the military (in this case, the U.S. Navy) in a period of rapid technological change a century ago seems all too familiar

It was hard to know how to fit them together into a new structure. But the disorder was not just the product of technological change. It was caused in greater part by the fact that the officers did not know what to do with what they had. There was in fact a great and raging debate as to purpose and mission. Since there was no apparent answer, officers did the obvious thing. First they went on building everything they could think of. The result was a collection of ships designed to fulfill a wide variety of intentions that did not fit together in a working way as a fleet. The hope was that if the performance of the parts could be improved, the whole would fit together and function better. So the officers set up boards to recommend improvements in the parts. There were boards on propellers, on boilers, on shells, on guns and engines and armor plates; there were boards on monitors and rams and destroyers and cruisers and ironclads and ships of the first, second, and third rate. There were from 1865 to 1890 over one thousand boards looking

at everything and, often at the same thing ... There was not much reduction of the prevailing confusion [7].

The trusty conventional approach used in the public and the private is to partition complicated matters so as to isolate the key problems and, then, to solve them one by one with "practical" solutions. This approach is the natural result of four decades of overspecialization -- the tendency of professionals to narrow their focus and for scientists to compartmentalize their knowledge.

National security, in general, and aircraft survivability, in particular, are metaproblems -- problems that entail variables from many academic, scientific and professional disciplines; involve the necessity to impose some sort of balance between two or more apparently competitive ends; and are generally susceptible to ethical interpretation. Metaproblems tend to remain outside of any formal problem solving discipline because the world is not structured in the same way that knowledge of it is. Interpreted with respect to the aircraft survivability phenomena : current military standards, handbooks and bibliographies represent far more convenient ways of organizing information than using it.

In contrast to the conventional approach is the systems approach. Here the idea is to aggregate the diverse issues and then to craft plans, often of long range, for dealing with the whole. In the absence of a systems approach based on a strategic premise, suboptimization governs what we do. Strategic thought is bankrupt in the United States. In the private sector corporate concern seldom goes beyond the next quarter's indicators; public officials limit their planning horizon to their terms

of office. Fragmentation of human resources due to overspecialization and a shrinking planning horizon have produced a substrategic perspective -- that is, orientations and decisions which make good sense when applied to a part of our system of security, but which are deficient when one takes the measure of the system as a whole.

The systems approach promulgated here is more than the techniques of scientific management applied to the fiscal side of defense planning in the 1960s and 1970s under the rubric "systems analysis". As implied by the term, its essence was analysis -- the division of problems into a number of separate and less baffling questions. A systems approach, in contrast, is synthetic in that a problem is not approached by taking it apart, but by first viewing it as a part of a larger problem. Systems analysis is then performed within this context [8]. The systems approach to aircraft survivability described in this research utilizes a model in which defense management and combat operations are seen to be as interdependent as the front and rear sights of a rifle. The job of optimizing or economizing cannot be separated from the tasks of making military decisions, i.e., choosing strategies and tactics.

1.7 SURMAN - A POLICY ASSISTING DEVICE

The past two decades have seen a tremendous expansion in the role and influence of computer models as a "policy assisting" device--first in the analysis of national security issues, and now, for the analysis of various problems arising in the affairs of Government. That the use of such models can be fruitful and rewarding is without question; but to view them only

as an extension of the "objective" tools of science and mathematics is a serious mistake. The "policy assisting" models differ from their engineering-accounting cohorts in ways that are subtle and yet nontrivial. The term "policy assisting model" connotes a computer model that (1) is used for the systematic examination or analysis of subjective problems (i.e., problems without a well-defined mathematical representation); and (2) is intended to influence high levels of Government decision-making. It includes models that are used by agency and executive branch officials, as well as models that influence congressional debate and action. Above all, the term describes a model that deals with questions beyond the purview of rigorous scientific deduction.

Many of the problems encountered in the classical sciences, engineering, or accounting, are rigorously quantifiable. Their structure is well-understood, and their mathematical formulas provide a clear-cut representation of the "real world" problem. A subjective problem, on the other hand, may be given a mathematical form that provides an unambiguous representation of the real world problem; but it must be conceded that the structure of portions of the phenomenon may be subject to differing opinions and parameter values may not be known precisely.

In 1983 the Civil Engineering Systems Policy Research Laboratory of Virginia Tech was awarded a research grant to develop and implement a survivability management model (SURMAN) for use by advanced program planners. The model details the essential survivability management parameters and their causal relationships throughout the life cycle of aircraft systems, and demonstrate the feasibility of obtaining a desired

level of functional capability through a given approach and the connection between current needs and future returns. Other aspects include the forecasting of macro-behavior, predicting consequences of proposed actions and failure to act, and the conducting of sensitivity analyses to establish research and data gathering priorities, as well as providing aids to communications among those concerned with survivability issues and in their understanding.

SURMAN consists of five submodels: (1) Economy Submodel, (2) Budget Submodel, (3) Procurement Submodel, (4) Attrition Submodel, and (5) Survivability Submodel. An increase or decrease in the value of decision variables in a submodel not only affects the parameter values through time in that submodel, but also dynamic parameter values in other submodels. For example, an increase in the Gross National Product increases the Federal Government Budget; an increase in Federal Government budget increases the DOD military budget which in turn increases the military spending powers. An increase in military spending results in a higher military buildup in terms of procurement, research and development, operations and maintenance, construction, etc. Finally, a higher military buildup results in greater national security in terms of military power.

When the controlled parameters in each submodel are traded-off using the combined model, those areas that are in critical need for improvement are identified. Then the proper actions can be taken to make those improvements that would lead to greater national security. For example, the spendings in research and development can be traded-off with spendings in procurements, operations and maintenance, construction, etc. among the services and among activities in each service to find the best

combination of force size, survivability, and availability of military combat aircraft.

The model also provides the opportunity for trading-off the aircraft survivability enhancement techniques and selecting those techniques that have higher benefits and lower penalties.

The scenarios that can be generated emphasize the macro-capabilities of the model. The model can perform survivability tradeoff analysis for seven generic vulnerability reduction techniques (shielding, redundancy, active damage suppression, passive damage suppression, component isolation, component elimination, and material hardening) and five susceptibility reduction techniques (signatures, countermeasures, tactics, performance, and threat suppression), applied to over a hundred generic components in eighteen subsystems, in response to five primary effects (ballistic impact or penetration of nonexplosive projectiles, ballistic impact or penetration of fragments from externally detonated missile warheads, external blast effects, internal blast effects, and high energy laser effects) and five secondary weapon effects (internal fires and explosions, hydraulic ram effects, and liberation of corrosive materials, high temperature gases, and toxic gases), inflicted by four types of small arms weapons, seven types of antiaircraft artillery, two types of airborne cannon, four types of airborne rockets, six types of airborne missiles, nine types of land-based surface-to-air missile, and four types of sea-based surface-to-air missiles. This is accomplished by linking subsystem routines within the "Survivability Submodel" to other aspects of the model [9,10].

1.8 PURPOSE AND OBJECTIVES

SURMAN is significant in distinguishing between what might be referred to as "inputs" and "outputs". It is believed that virtually the entire defense debate concerns itself not with wartime outputs, but with peacetime inputs -- static inventories of men and machines, often called "bean counts" in the defense establishment. Too little attention is paid to the operational factors involved in taking those peacetime inputs and producing a wartime output -- achieving military goals. SURMAN integrates inputs (aircraft inventories), technological factors (aircraft survivability and target destruction capability), and operational factors (aircraft availability and sortie rate) in such a way that they can be brought to bear on output. Each of these must be a component of analysis : their isolated treatment cannot come to grips with the real issue.

SURMAN accomplishes the above by assessing the impacts of policy options and design/modification alternatives. The policies and designs are the inputs to the model and the impact measurements are the outputs. The problem is that it is rarely possible to consider an adequate range of alternatives and even more difficult to organize feedback to analysts and decision makers for new alternatives to be generated in the light of predicted impacts of earlier experiments.

The purpose of the research described in this thesis is to sharpen and focus the ability of SURMAN to perform its policy/design evaluation function by "encapsulating" the existing model. The idea is to overcome the long-recognized combinatorial problem of large-scale computer models -- how to set-up, search and evaluate the impacts of the vast number of

options in policy space. Complimentary objectives are to render the existing model more accessible to potential users by making it compatible with simpler computers other than the main-frame installations upon which it was developed at Virginia Tech, and the one in which it was implemented at the Naval Air Systems Command in Washington, and to make the power of the model available to decision-makers with neither the time nor the hardware needed to experiment with the model. To accomplish these objectives two elements of the plan of research that were formulated were : (1) to develop a personal computer version of SURMAN and (2) to present information relating inputs and outputs graphically using curves derived from experimentally designed computer runs.

Chapter 2 provides background into the combat aircraft survivability phenomenon and the system dynamics methodology used in the development of SURMAN, and the satisfaction of the requirements of this research. Chapter 3 offers a description of the P.C.SURMAN model developed here. Chapter 4 focuses on what is believed to be the main contribution of this research to combat aircraft conceptual design -- survivability tradeoff analysis.

2.0 THE PHENOMENON AND THE METHODOLOGY

2.1 INTRODUCTION

The ultimate combat survivability assessment is the level of attrition, or loss of mission capability, which occurs when the aircraft or missile system undertakes missions in an active and aggressively hostile environment. If attrition is low, and if the mission capabilities are successfully demonstrated, the system will be effective and the design is good. However, if attrition is higher than expected, it is too late to do anything about it, and there will be serious shortcomings in either the capability to achieve the combat objectives or in the ability to sustain the force in a hostile environment.

There is, therefore, an obvious need for combat survivability testing and analysis capabilities. The costs of testing and the availability of test hardware, particularly during design and development, make an analytic assessment capability imperative. Furthermore, this analytic capability must be as thoroughly validated as possible. It must be recognized and accepted as a standard, must be cost effective, and must be available to the entire aircraft development community.

2.2 AIRCRAFT SURVIVABILITY EVALUATION

To begin with it is necessary to establish three basic definitions. The first is the definition of survivability. It includes all factors that

affect the potential attrition or loss of mission capabilities. The other two terms are susceptibility and vulnerability and their definitions are specific within the air combat survivability discipline. Susceptibility comprises all the capabilities and characteristics, of both the aircraft and the threat, that influence or determine the probability that the air target is hit. It includes the consideration of all parameters that influence the threat capabilities to detect, lock on, track and fire at the aircraft or missile and the capabilities of this airborne target to evade the threat. Vulnerability is the measure of the effect on the capabilities to continue controlled flight, perform mission functions, and recover the system at a land or ship base. It is the response of the aircraft (or a missile system) given a hit by the damage mechanism of a threat weapon [6].

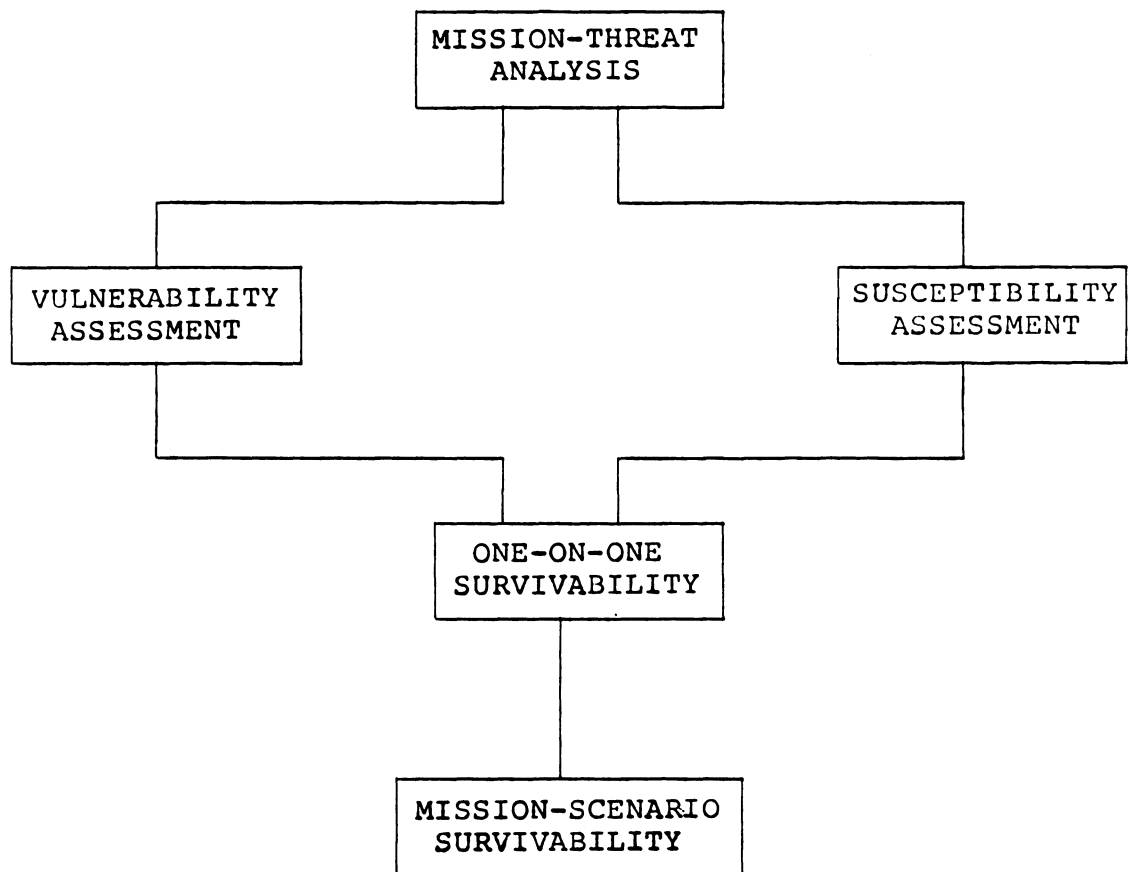
Survivability encompasses all aspects of accomplishing flight missions against threat weapons, without unnecessary loss or damage to aircraft, including crew and payload. It includes threat avoidance tactics and countermeasures, as well as damage resistance and tolerance. As a design discipline, survivability involves the technology and formal documentation to guide the procurement, design and modification of aircraft for implementation of cost/mission effective survivability enhancements. Since both aeronautical technology and enemy threat are continually evolving, the need to continue survivability enhancement efforts persists. In practice, survivability assessment is employed whenever there is a modification to the design, a change in mission, or a change in threat.

While it is widely recognized that survivability engineering and management deal with a continuous process, the dynamic, interactive, feedback aspects are not fully appreciated. While it is stressed that the most effective application of survivability is early in the design stage as an optimization tool in the total series of iterations and compromises in the design process, it should also be mentioned that, unless flexibility has been incorporated, herein lie the greatest risks.

Currently, the two principal elements of aircraft combat survivability evaluation are (1) survivability assessment and (2) survivability tradeoff analysis. A survivability assessment is the systematic description, delineation, quantification, statistical characterization, and the computational methods and measures of the survivability of an aircraft in encounters with hostile defenses. Survivability tradeoff analysis is the evaluation of survivability enhancement techniques that not only affect the principal survivability contributors, such as signatures, countermeasures and inherent vulnerability, but may also affect vehicle performance, mission effectiveness and program life-cycle cost including those resulting from projected combat attrition.

2.3 SURVIVABILITY ASSESSMENT PROCESS

The major elements of the survivability assessment process are shown in Figure 2.1. An analysis of the missions to be flown in the tactical and physical scenarios supports both a vulnerability assessment and a susceptibility assessment. The results of the vulnerability and susceptibility assessments allow the determination of the survivability



**SURVIVABILITY
ASSESSMENT PROCESS
Fig. 2.1**

of the aircraft or the missile against a single weapon. These single encounter survivabilities are then combined at the frequencies predicted by the mission-threat analysis in the mission scenario survivability assessment. A brief overview of each of each of these analytical assessment steps will be given [5].

The mission-threat analysis determines the frequencies and geometrics of the interactions between the aircraft or missile and the threat weapon. Each threat to which the system will be exposed is identified and described in terms of the data required for the vulnerability, susceptibility and survivability assessments.

The aircraft variables that influence survivability include those that govern detectable signatures; the countermeasures capabilities, both active and passive, as applied to specific weapon types; the speed, altitude ceiling, low-level flight, and maneuver capabilities; and the vulnerability, or response of the system given that it is hit. These all affect the mission-threat analysis and the subsequent evaluation phases.

There generic characteristics associated with each of the types of weapons. The threat can be categorized as surface-to-air or air-to-air with subcategories for each. Within the air-to-air category, it is convenient to group the threats into a set employed in short- or medium-range combat and a set for long-range intercepts. The mid-to-short-range threats are generally characterized by a combination of missile and gun type weapons carried by high performance aircraft. An excursion from this generalization is the armed helicopter employed in air-to-air role. The missiles are a combination of infrared(IR)-guided and radar-guided and are generally smaller than the other missile threats

both in terms of total mass and individual fragment size. The missiles are generally designed for high maneuver capabilities. The long-range intercept threat relies on detection and track at sizeable standoff ranges with the terminal encounter capability built into the missile. Detection is by radar with possible terminal guidance by other operating modes. The missiles are large with warheads designed to be effective at miss distances larger than would be expected for short- or medium-range threats. Denial of acquisition or track is an important consideration with long-range threat.

Surface-to-air threats include hand-held weapons, crew-served machineguns, antiaircraft artillery and surface-to-air missiles. Attrition against hand-held weapons, which were major causes of losses in Southeast Asia, should be essentially preventable. The crew-served weapons include dual purpose machine guns up through the 23mm and the 30mm gun systems. Countering these simple weapons is primarily through performance, maneuverability and tactics along with a considerable potential for reducing the vulnerability given a hit.

Antiaircraft artillery includes all weapons from the World War II vintage 37mm through the 130mm guns. The smaller calibers (37mm through 76.2mm) are contact-fuzed and require a direct hit on the aircraft or the missile. Given a hit, they are highly effective. The larger weapons employ proximity fuzes and rely on the combined of blast and fragmentation. The weapons are either land- or ship-based. Because of the potential lethality of a direct hit or a properly fuzed proximity burst, protection must emphasize a combined approach of threat detection, maneuver, countermeasures and vulnerability reduction.

As with gun systems, surface-to-air missiles are found both in land and ship environments. The more sophisticated systems employ either radar or infrared tracking with an alternate optical or electro-optical mode. The warheads are large and highly lethal at near miss distances. Survivability requires a countermeasure or tactic that denies acquisition or tracking, or increased miss distances, along with vulnerability reduction that effective against all but the close-in warhead detonation. Low level penetration is also frequently effective [11].

Referring to Figure 2.1, the mission-threat analysis provides required input data and assessment conditions for both the vulnerability assessment and the susceptibility assessment. The vulnerability assessment examines, at the appropriate level of detail, the response of the aircraft or missile and its subsystems to the damage mechanisms of the threat weapons. The determination of vulnerability indices such as "vulnerable areas" or "probability of kill given a hit" develops the desired quantified measures of vulnerability.

A major phase of the assessment process is the susceptibility assessment. This is usually conducted concurrently with the vulnerability assessment. The susceptibility assessment, addresses all the factors that lead to the determination of the probability of hit. The susceptibility assessment is a time and geometry-related assessment that predicts the capabilities of threat weapon systems to acquire, lock-on, track, and hit the airborne target. Capabilities include identification, necessary command and control, and the handoff of the target from one system to another. This process, which leads to the terminal encounter,

may be in the presence of countermeasures and usually involving an aircraft employing evasive tactics.

The parameters of susceptibility are those of the threat and the aircraft or missile that influence the acquisition, track and intercept processes. The threat parameters are measures of capabilities of the threat systems. The aircraft parameters of importance are the detectable signatures, any employment of countermeasures, and the capabilities to maneuver during the attempted tracking by the threat weapon. Tactics are an important measure of the aircraft's or missile's performance capabilities.

Returning to Figure 2-1, the results of the vulnerability and susceptibility assessments, along with data from the mission-threat analysis, are employed in the survivability evaluation of the aircraft in an engagement with a single threat weapon system. Aircraft vulnerability data and the probability of hit parameters from the susceptibility assessment are combined with data that define the geometry and conditions of individual encounters to provide probability of kill (P_K) and probability of survival (P_S) relationships for the single aircraft or missile flying into the effective envelope of a threat weapon. This is done for each type of weapon defined in the mission-threat analysis. The results are most frequently developed as a function of performance parameters such as speed or maneuver load factor, or engagement geometry such as altitude or standoff distance.

The final step in the survivability assessment (see Figure 2-1) is the determination of the survivability of the aircraft or missile as it

performs its missions in the threat environment. This assessment also provides the baseline for survivability enhancement tradeoff studies.

2.4 THE MATHEMATICS OF SURVIVABILITY

Survivability is the capability of a weapon system, such as an aircraft, to continue to carry out its designated mission in a combat environment. It is a function of both susceptibility, the combination of factors that determine the probability of hit by a given threat and vulnerability, the extent of degradation of a system after having been intercepted by a threat propagator. Symbolically,

$$\text{SURVIVABILITY} = 1 - \text{SUSCEPTIBILITY} \times \text{VULNERABILITY} \quad (2.1)$$

with all three parameters expressed as probabilities.

Actually the probability of survival is a summary measure and, depending on the particular application, may be computed for various aspects of a mission or a complete mission. Two popular parameters are the probability of survival per sortie, P_{SM} , and the probability of survival per encounter, P_{S/E_i} . The probability that an aircraft will survive a single operational flight or sortie during which it may have multiple engagements with the various weapons of a zone defense is given in [5] [6] by

$$P_{SM} = \prod_i \exp \left\{ - \left(N_i \times D \times R_{\text{eff}_i} \times (1 - P_{S/E_i}) \right) / A_i \right\} \quad (2.2)$$

where

P_{SM} = probability of mission survival over i^{th} engagements
with the zone defense weapons mixture

A_i = the area in which the weapon systems or firing units
are expected to be randomly distributed

N_i = the number of i^{th} type weapon systems in area A

R_{eff_i} = the effective range of the i^{th} type weapon system

D = the distance the aircraft flies through area A
without significantly changing altitude or airspeed

P_{S/E_i} = the probability of the aircraft surviving a single
encounter with the i^{th} type of weapon system.

All of the above parameters with the exception of P_{S/E_i} are
environmental oriented. The probability of survival per encounter can
be shown to be

$$P_{S/E_i} = 1 - (P_{LOS})(P_D)(P_L)(P_G)(P_{DET})[1 - \pi(1 - P_{SSK})]^n \quad (2.3)$$

where

P_{LOS} = probability of line-of-sight to the target

P_D = probability of detection, given line-of sight

P_L = probability of launch or firing, given detection

P_G = probability of successful guidance, given launch or firing

P_{DET} = probability of warhead detonation (fuzed warheads),
given successful guidance

n = number of shots fired during a pass

P_{SSK} = single-shot kill probability

A number of essential functions must be performed in sequence by any type of anti-aircraft system to be effective. First, a radar or visual line-of-sight to the target must exist. Next, the target aircraft must be detected, recognized, and identified as an enemy. Projectile or missile launch can then occur given that the target is within its range and angular-rate limitations. Successful guidance to the target is a function of the defense system type, the launched projectile or missile associated with the defense system (i.e., free flight projectile, radar or IR guided, etc.), and the kinetic aspects of the target. Referring to equation 2.3, the five terms preceding the bracketed term represent the threat system effectiveness, TSE. Since it is the product of five probabilities, it is itself a probability, P_{TSE} . Rewriting equation 2.3

$$P_{S/E_i} = 1 - P_{TSE} [1 - \pi(1 - P_{SSK})]^n \quad (2.4)$$

The form for P_{S/E_i} can be derived as follows [12]

$$P_{S/E_i} = 1 - P_{TSE} \times P_{K/TSE} \quad (2.5)$$

where $P_{K/TSE}$ is the probability of being killed for a certain threat system effectiveness. Using the binomial distribution with parameters n (the number of shots fired) and P_{SSK} (the single shot kill probability).

$$P_{K/TSE}^{(x)} = \sum_{x=1}^n \frac{n!}{x!(n-x)!} (P_{SSK})^x (1 - P_{SSK})^{n-x} \quad (2.6)$$

This is one minus the probability of not being killed in n shots,

$$P_{K/TSE}(x) = 1 - P_{K/TSE}(0) = 1 - (1 - P_{SSK})^n \quad (2.7)$$

Substituting (2.7) in (2.5) gives

$$P_{S/E_i} = 1 - P_{TSE} + P_{TSE} \times \left[\pi (1 - P_{SSK}) \right]^n \quad (2.8)$$

Only if P_{TSE} equals one is equation 2.4 (and therefore equation 2.5) correct.

Repeating the derivation under the assumption of a Poisson distribution, equation 2.6 becomes

$$P_{K/TSE}(x) = \sum_{m=1}^{\infty} e^{-m} \frac{m^x}{x!} \quad (2.9)$$

where $m = n \times P_{SSK}$. Instead of (2.7), one now obtains

$$P_{K/TSE}(x) = 1 - P_{K/TSE}(0) = 1 - e^{-n P_{SSK}} \quad (2.10)$$

Substituting (2.10) in (2.5) gives

$$P_{S/E_i} = 1 - P_{TSE} + P_{TSE} \times e^{-n P_{SSK}} \quad (2.11)$$

Equation 2.11 is an approximation of equation 2.8 just as the Poisson is an approximation of the binomial distribution. That is

$$\pi (1 - P_{SSK})^n = (1 - P_{SSK})^n = \left[(1 - P_{SSK})^{-1/P_{SSK}} \right]^{-n P_{SSK}} = e^{-n P_{SSK}} \quad (2.12)$$

In order to get the popular forms of equation 2.1 which is

$$P(\text{survival}) = 1 - P(\text{detection}) \times P(\text{hit/detection}) \times P(\text{kill/hit})$$

we can take equation 2.11, expand the last term into an exponential series, neglecting higher order terms --

$$P_{S/E_i} = 1 - P_{TSE} \times n P_{SSK} \quad (2.13)$$

where

$$P_{SSK} = P_{SSH} \times P_{K/H} \quad (2.14)$$

and

$$P_{S/E_i} = 1 - (P_{TSE})^{(nP_{SSH})} (P_{K/H}) \quad (2.15)$$

Substitution of (2.15) into (2.2) gives the expression for mission survivability

$$P_{SM} = \pi \exp[-(ZDF)(P_{TSE})^{(nP_{SSH})} (P_{K/H})] \quad (2.16)$$

where $ZDF = N_i D \times 2R_{eff_i} / A_i$ and can be thought of as the "zone defense factor" as implied by the parameter definitions given in equation 2.2.

The degree of sophistication employed in an analysis of defense system effectiveness depends on the intended use of the results and the confidence level placed on the inputs. Realistic results required the inclusion of many parameters, some of which such as aircraft vulnerability areas, blast and fragmentation envelopes, weapon system accuracy, etc., are illusive. Consider the last term of (2.15): the probability of a random hit killing the aircraft is equal to the ratio of its vulnerable area A_V to its presented area A_P . Substituting in (2.15) gives

$$P_{S/E_i} = 1 - P_{TSE} \times n \times P_{SSH} \times A_V / A_P \quad (2.17)$$

Now consider P_{SSH} in equation 2.15, the probability of hitting an aircraft in a single firing from a threat. This single shot probability determination can be approached in many ways including the following. Using the concept of CEP (the circular error probability of a group of n shots defining a circle within which half will hit) the probability of the aircraft being hit [13]

$$P(x) = \frac{m^x}{x!} e^{-m} = \frac{m^x}{x!} (1 - m + \frac{m^2}{2!} - \dots) \quad (2.18)$$

where

$$m = \frac{A_P}{\pi(CEP)^2} x_1 x_2 \quad (2.19)$$

Neglecting higher order terms in the exponential expansion,

$$P_{SSH} = \frac{A_P}{2\pi(CEP)^2} \quad (2.20)$$

and after substituting in (2.15)

$$P_{S/E_i} = 1 - P_{TSE} \frac{n A_V}{2\pi(CEP)^2} \quad (2.21)$$

It is interesting to note that the development in equations 2.3 to 2.21 define the look-shoot, look-shoot case. For the look-shoot-shoot-shoot, etc. case, the Bernoulli form is

$$P(x) = \binom{n}{x} (P_{TSE} \cdot P_{SSK})^x (1 - P_{TSE} \cdot P_{SSK})^{n-x} \quad (2.22)$$

giving a probability of survival per encounter of

$$P_{S/E_i} = (1 - P_{TSE} \cdot P_{SSK})^n \quad (2.23)$$

2.5 MISSIONS AND AIRPLANES

It is appropriate to pause at this point and reflect. What is meant by tactical airpower? What military objectives does contemporary U.S. doctrine call upon to accomplish and what sorts of aircraft are needed for these purposes? Without consideration of these issues, it is impossible to develop an appropriate policy assisting tactical airpower model.

Air power theorists have traditionally distinguished two general spheres of air operations: strategic and tactical. In the prenuclear era the objective of strategic air attack was to wear down the enemy's will and ability to resist by striking at the foundation of the socioeconomic structure -- the morale of the civilian population and the means of production. Repeated attack by massive air armadas was the instrument used to advance these goals. Today, with the tremendous destructive potential of nuclear warheads and the high confidence each side enjoys in the ability of its delivery systems to penetrate the other's defenses, this objective is no longer relevant. The strategic mission has become one of deterrence. The high cost of strategic bombers would in most cases prohibit their sustained use to deliver conventional munitions against modern air defenses, therefore their task now falls on the tactical air forces.

Troops, guns, and tanks tend to fight against their mirror images. The same tanks can be used offensively, to intrude into enemy lands, or defensively to guard the homeland. The demands of air combat, in contrast, tend to force distinct designs on aircraft intended for differing tactical roles. Tactical airpower can be divided into two groups: planes that attack surface targets and those that fight other airplanes. Each group can be further divided according to range -- short, medium and long. A brief description of the functions and types of aircrafts suitable for performing them is presented [14].

Attack aircraft are designed to search out, attack, and destroy enemy land or sea targets, using conventional or special weapons. Fighter aircraft are designed to intercept and destroy other aircraft and/or missiles and include multi-purpose aircraft designed for interdiction. The multiplicity of activities that current U.S. doctrine calls on the tactical air forces to perform may be grouped into seven major categories : counter air, interdiction, close air support, aerospace defense, airlift, reconnaissance, and electronic warfare. Counter air is usually thought of as operations designed to acquire and maintain air superiority. From the standpoint of the aircraft performance requirements, the extent and degree of air superiority to which doctrine aspires -- over only friendly, over contested, or over hostile territory -- is of critical significance.

Air interdiction is the mission normally thought of belonging to an attack aircraft or lighter bomber, in that unlike nationwide strategic attack it is localized and not on as large a scale. Still, attack aircraft suitable for interdiction tend to be very costly. They must

travel far with heavy load of munitions, so they are large and heavy. At the same time, they are on the tactical offensive flying over enemy land with well-prepared and massed defenses which requires that they be fast and have means of self-defense. This combination of requirements places high demands of performance; moreover, the interdiction mission is becoming increasingly difficult, risky, and costly as surface-to-air missiles improve.

In contrast to the long distances typical of interdiction, close air support aircraft attack enemy ground forces near their own ground troops and in support of them. The aircraft can be relatively slow, of light-to-medium weight, able to bomb and strafe infantry, cannon, tanks, and strong points. Armed helicopters as well as fixed wing planes armed with antitank weapons, can perform this mission. Since fixed wing attack aircraft, to say nothing of the slower helicopters, cannot survive long if faster fighters are around in numbers, air superiority becomes a critical factor.

Aerospace defense for long range interception can be seen as a special case of the air superiority mission, differing in emphasis in two respects : First, it is aimed at stopping not so much enemy fighters as attack or bomber aircraft which tend to be slower and less maneuverable. Second, this mission is more closely tied to the tactical defensive -- meaning short-range -- operations around the perimeter of a country or longer flights to intercept strike aircraft farther from the border. Aircraft especially designed for interception have not been particularly important in the U.S. force structure ; however, in Europe and the Soviet Union they play a much more important role in the tactical air forces.

More and more special roles are appearing for tactical aircraft. These include airborne warning by radar and radio; reconnaissance by photographic image and electronic means; electronic warfare and the countermeasures to it (jamming, disruption, or attack of radar installations and the like); and air control aloft, coordinating the operations of warning, reconnaissance, and fighter and attack aircraft. Specially equipped fighter and strike aircraft perform these missions deep into enemy territory.

2.6 SURVIVABILITY-ATTRITION CONCEPTS

Aircraft attrition is dependent on many factors including the susceptibility of the aircraft to detection and hit; the vulnerability of the aircraft once it is hit; the type, number, and placement of enemy defenses; and the tactics and countermeasures as its disposal. When an aircraft penetrates a specified threat scenario, its survival probability P_S can be estimated from the aforementioned considerations. Then the probability that the aircraft gets killed P_K , or its attrition, is $1 - P_S$.

We begin our mathematical treatment of the subject by developing the expression for the cumulative number of sorties flown CS by an aircraft with survivability probability P_S after n scheduled sorties, which is given by the following geometric series:

$$CS = 1 + P_S + P_S^2 + P_S^3 + \dots + P_S^{n-1} \quad (2.24)$$

Multiplying both sides by P_S gives

$$P_S \times CS = P_S + P_S^2 + P_S^3 + \dots + P_S^{n-1} + P_S^n \quad (2.25)$$

subtracting (2.25) from (2.24), and solving for CS, one obtains

$$CS = (1 - P_S^n) / (1 - P_S) \quad (2.26)$$

Taking the limit as n approaches infinity, the expected number of sorties scheduled by an aircraft in its lifetime is

$$E(n) = 1 / (1 - P_S) \quad (2.27)$$

Frequently, measures of effectiveness are expressed in term of "exchange ratios". An example of an exchange ratio is the number of targets destroyed per aircraft lost TDPL, expressed as

$$TDPL = E(n) \times TDPS \quad (2.28)$$

where

TDPS is the number of targets destroyed per sortie [15].

There are two important shortcomings of this time invariant approach for determining attrition measures of effectiveness. First, knowing how fast a given number of targets can be destroyed is as important as knowing the ultimate number destroyed. Secondly, attrition and the threat responsible for this attrition are not constant, but change over time. Compile [16] overcomes the first shortcoming by bringing time into the picture as follows:

$$n = SR \times t \quad (2.29)$$

where SR is the sortie rate. The sortie rate, a complex function involving maintenance, repair time, reliability, crew ratio, etc., is assumed to be constant. Using (2.29) the cumulative sorties flown by an aircraft with survivability P_S and sortie rate SR in t days is

$$CS = (1 - P_S^{SRxt}) / (1 - P_S) \quad (2.30)$$

The cumulative sorties flown by a force of N aircraft, CS_N , is obtained by multiplying (2.30) by N:

$$CS_N = N (1 - P_S^{SRxt}) / (1 - P_S) \quad (2.31)$$

The cumulative targets destroyed by a force of N aircraft, T_N , is obtained by multiplying (2.31) by the target kill potential TDPS:

$$T_N = (TDPS)(N)(1 - P_S^{SRxt}) / (1 - P_S) \quad (2.32)$$

Other parameters that can be obtained from the above relations are the function of force remaining FFR and the fraction of force lost FFL which are defined as follows:

$$FFR = P_S^{SRxt} \quad (2.33)$$

$$FFL = 1 - P_S^{SRxt} \quad (2.34)$$

Let us begin by expressing the fraction of force remaining FFR in (2.33) in alternate forms:

$$FFR = P_S^n = [(1 - P_K)^{-1/P_K}]^{-nP_K} \quad (2.35)$$

As n approaches infinity, the base of natural logarithm is defined so that with substitution for n and P_K we obtain

$$FFR = e^{-nP_K} = e^{-(1 - P_S)(SR)(\tau)} \quad (2.36)$$

Recognizing that

$$FFR = \$/_t / \$_0 \quad (2.37)$$

where $\$/_t$ is the number of aircraft at time t and $\$/_0$ is the initial value for this variable, we see that (2.36) is really the solution to the differential equation,

$$\frac{d\$/_t}{dt} = (1-P_S)(SR)(\$/_t) \quad (2.38)$$

Expressed as an integral equation, (2.38) becomes

$$\$/_t = \$/_{t-1} - \int_{t-1}^t (1-P_S)(SR)dt \quad (2.39)$$

Converting to a system dynamics formulation (to be explained in the next section),

$$\$/_K = \$/_J - (DT)(AR\$.JK) \quad (2.40)$$

where $AR\$/$, the attrition rate is given by

$$AR\$.KL = (1-S\$(SR\$(\$.K) \quad (2.41)$$

The advantages of a system dynamics formulation of the aircraft combat attrition phenomenon over the discrete-event representation of the preceding sections is that it permits the incorporation of much more realism. For example, attrition due to both surface threat and air threat platforms can be considered simultaneously. This is important because it recognizes that the threat, and therefore attrition inflicted by the threat, will change from sortie to sortie in a real situation. Indeed, many aircraft are designed specifically for counterair missions so as to reduce enemy air-launched threat propagators (e.g., enemy combat aircraft with air to surface and air to air missiles).

2.7 COMPUTER SIMULATION MODELING

The past decades have seen the emergence of what we refer to in Chapter 1 as the systems approach. The systems approach is a procedure which attempts to be rational and objective -- much like the classical scientific method -- in approaching complex problems. This approach, at first successful in military, industrial and managerial contexts, has now become firmly embedded in practically every discipline which tries to describe or predict observable phenomena such as aircraft survivability. An important step in the systems approach is the development of models.

Model building is the best way to understand complex relationships within a system. A model is an abstraction of reality and can be conceptually regarded as a substitute for the real system. It is meant to capture the functional essence, but not necessarily the detail of the system. Indeed, in this research we substitute a simpler personal computer model for a much more detailed main-frame computer model to force ourselves to reduce the amount of detail. Thus, instead of investigating and experimenting with the real option, we can interrogate the model -- usually with less risk, less time and less money. A model permits experimentation among alternative policy strategies and can test the consequences of assigning different values to the variables involved.

There are many types of models. However, most decisions are made and policies formulated by the interpretation and application of mental models -- with all their limitations. Mental modeling is a natural capability and it can be powerfully adopted to meet changing circumstances by skilled practitioners. However, there are other types of models that

can also make contributions to the study of complex systems and the formulation of policy stemming from such analysis. They include physical models (scale and analog) and symbolic models (verbal and mathematical) [17].

It is the mathematical model that is most closely associated with the systems approach. Three characteristics of mathematics that make the use of these models attractive are: (1) they are very precise in that little ambiguity is present in the meaning of mathematical symbols, (2) they are concise in that they require relatively few symbols to express relatively complex ideas and behavior, and (3) they are easier to manipulate than words by those who understand mathematical procedures.

In order to understand and utilize mathematical models, it is necessary to be aware of a few of their essential features. Mathematical models are constructed by formulating equations which describe system components and system states. Equations, in turn, are composed of variables, constants and parameters. Variables that are arbitrarily assigned fixed values for the purpose of experimentation. If the value of a variable is determined by conditions in the environment it is known as an "exogenous variable". If the system determines the values of a variable it is known as an "endogenous variable". [18]

A special class of mathematical models is referred to as simulation models. There are two interpretations regarding the term simulation: it may be restricted to referring to the process by which a model is solved or it may refer to both the process by which a model is constructed and solved. For the particular methodology used in this research, system dynamics, the latter, more general, interpretation holds. Irrespective

of this interpretation chosen, a simulation consists of the construction of a state (system) history -- previously described as a succession of state (system) descriptions. The simulation model employs mathematical symbols to represent the interactions of system components at different points in time.

Thus, simulation models are dynamic models. They involve changes in the state of the system through time. A simulation model expresses the dynamic relationships among variables. If changes in their values tend to produce proportionate changes in the values of the model outputs, the model is said to be linear; if not, the model is nonlinear. If it is assumed that the exact values of all variables can be computed and the values of all parameters are known, the model is "deterministic" as opposed to being "stochastic". Another important characteristic of a simulation model is the level to which it aggregates the real system -- sometimes described in terms of the words "micro" and "macro". Lastly, a simulation model which uses the large manipulative and tabulational capabilities of modern computing machines is called a "computer simulational model" [19].

2.8 SYSTEM DYNAMICS METHODOLOGY

The simulation of complex systems demands a good understanding of computer programming. The program employed should facilitate debugging, modification, and testing. It should also have easy reporting facilities and be problem-oriented rather than program-oriented making it easy to use by analysts and decision makers and as free as possible from the "cult

of the professional programmer". Over the years a number of special simulation languages have been developed either on their own or as generalizations of special purpose programs. One such language is DYNAMO, a computer software package closely associated with the system dynamics methodology.

System dynamics, developed by Professor Forrester of M.I.T., is a methodology that deals with deterministic, dynamic, non-linear, closed boundary systems. Its initial application in 1961 was to the study of the behavior of industrial systems where the short-term dynamics of production rates and inventory levels were analyzed [20]. Forrester expanded his system dynamics techniques in Principles of Systems in 1968 [21]. More recently he has applied his modeling methods to longer term problems of the city [22] and to the problems of world growth [23]. Currently, Forrester is developing a dynamic model of the United States economy.

As its name implies, system dynamics is a method of dealing with questions about dynamic tendencies of complex systems -- that is, the behavioral patterns they generate over time. System dynamicists are generally unconcerned with precise numerical values of system variables as specific points in time; they believe that correctly predicting a reversal of a trend is of much greater practical importance than correctly predicting the rate of continuation of a trend. They are much more interested in general dynamic tendencies; whether the system as a whole is stable or unstable, growing, declining, oscillating, or in equilibrium. Models commonly used in economics have proved quite unsuitable as a means of detecting economic cycles, defining the

conditions in which upheavals may occur, and subsequently of suggesting such an eventuality to the analyst.

System dynamics is based on the foundations of (1) decision making, (2) feedback systems analysis, and (3) simulation. Considering each briefly here and then in more detail later, decision making is stating how action is to be taken. Feedback deals with the way information is to be used for decision making. Simulation permits decision makers to view the implications of their decisions over the future. System dynamics, then, is a method of analyzing problems whose variables change over time, which permits the analysts to determine how the system (a firm, a city, a country) responds to factors within the decision makers control such as policy, organization and system structure, and outside of the decision makers control such as seasonal fluctuations, random variations, competition, and sudden change due to external shocks.

Essentially then, if we classify system methodologies as being (1) optimization-oriented, (2) casual, and (3) causal, system dynamics falls in the third category. Believing that most contemporary problem are so complex that it is foolish to think of a "best" solution, we shall not dwell on optimization. Causal approaches include: (1) "rules of thumb," (2) analogies, (3) naive algorithmic techniques, (4) correlation-type methods. Features of correlation are that relations between system variables are developed by applying mechanical mathematical procedures to data. Some shortcomings include the following: (1) many different, even contradictory, models may each fit the observed data equally well; (2) it is virtually impossible to choose between competitive correlation models on statistical grounds; and (3) since they are static models, they

can only provide an indication of what may happen if no changes are made in the system -- a serious constraint since that is precisely why one undertakes system analysis, to decide how to change the system so as to improve operation. System dynamic deals with the analysis of change [24].

2.9 THE MODELING PARADIGM

System dynamics is a modeling paradigm -- a system of rules which guide scientific inquiry. It provides a foundation for constructing computer models to do what the human mind cannot do -- rationally analyze the structure, interactions, and modes of behavior of complex social systems thus providing a framework whereby strategies can be tested and trade-offs performed while options are still open. The steps are: (1) the formulation of mental model in the form of a verbal description, (2) the expression of this verbal model in the form of a flow diagram, and (3) the conversion of this flow diagram in a set of simultaneous difference equations. These equations can be solved manually but this is not practical; a digital computer is necessary.

The system dynamics approach begins with an effort to understand the circumstances that have created a problem and continue to sustain it. Relevant information are collected from literature and knowledgeable persons close to the problem such as managers, customers, workers, experts, etc. As soon as a rudimentary measure of understanding has been achieved, a set of complementary forms of a model of the situation is developed.

The first step in developing the flow or causal diagram of the model is to identify the key variables which describe the problem situation and record the way the system to be analyzed works. These key variables which are deduced from a mental model or verbal description of the system, are arranged on a sheet of paper. Cause-effect relationships between pairs of variables are depicted by arrows in the second step. The third step in developing a causal diagram is giving each link or arrow a plus or minus directional sign usually placed near the arrow head.

Thus, to begin the causal diagramming process, the key variables that record the system behavior are identified from the verbal description of the problem. These key variables are then connected by arrows to show the cause-effect relationship. The variable at the head of the arrow is the dependent variable and the one at the tail is the independent variable. The variable at the tail of the arrow influences the variable at the head of the arrow. The causal relationship can also be understood as the variable at the tail of the arrow affects or causes the variable at the head of the arrow depending upon the context. One point to be borne in mind is that the pair-wise relationship is made under the assumption that "all other things being the same". The next step is to identify and mark the nature of the cause-effect relationship. If the relationship is one in which there is a direct proportionality between the two variables, then a plus sign is placed near the head of the arrow. This indicates that an increase in the value of variable at the tail of the arrow causes an increase in the value of the variable at the head of the arrow. A minus sign is placed at the head of the arrow when there is an inversely proportional relationship between the two variables, i.e., when

an increase in value of the variable at the tail of the arrow causes the value of the variable at the tail of the arrow causes the value of the variable at the head of the arrow to decrease and vice-versa.

There are two basic components of the structure and a system from the system dynamics perspective -- flows and levels. Levels are state variable that represent the accumulation or build up of resources in the system such as inventories of goods, persons, houses, and jobs. Rates of flow represent the activities and decision functions in the system such as movement of goods, births and deaths, construction and demolition of houses, hiring and firing of workers, etc. The flow can be categorized into two types: 1. physical flow and 2. information flow. Physical flows are causal relationships between a rate variable such as production rate (cars/week) and a level variable such as inventory (cars). Solid lines are used to indicate physical flows. The relationship between a level variable such as an inventory and a rate variable such as production rate is an information flow. It is the information regarding the state of the inventory that influences the production rate. Such relationships depicting information flow are represented using dotted lines [25, 26]. Thus level variables will always appear at the head of solid arrows and rate variables always appear at the tail of solid arrows. Any intermediate variable on the path from a level variable or exogenous input to a rate variable is called an auxiliary variable. Supplementary variables do not form a part of the system itself, but merely indicate its performance and therefore appear always at the head of a dashed arrow, and having no arrows emanating from them. Exogenous inputs, have no arrows leading to them but have dashed arrows emanating from them.

The next step is the translation of the visual model, the causal diagram, to a mathematical model, the system of equations.

2.10 SYSTEM DYNAMICS EQUATIONS

Integration (or accumulation) is the basis of the level and rate structure used in system dynamics. A level variable $L(t)$ denotes the accumulation of some physical entity at time t . RI and RO represent the rate variables, rate-in and rate-out, denoting the change in the level variable over the interval from $t-1$ to t . The relationships between the level $L(t)$ and the rates can then be expressed as

$$L(t) = L(t-1) + \int_{t-1}^t (RI-RO) dt \quad (2.42)$$

$$L.K=L.J+(DT)(RI.JK-RO.JK) \quad (2.43)$$

In difference equation terminology, any level variable L_i is expressed as functions of rate variables R_j and the previous value of the level,

$$L_i(t) = L_i(t-1) + (dt) \sum_{j=1}^n R_j(t-1) \quad i=1, \dots, m \quad (2.44)$$

with the R_j 's assumed to be constant over the interval from $t-dt$ to t .

The rate variables are of the form

$$R_j(t) = f[L_i(t), E_k(t), A_{ij}(t), A_{kj}(t)] \quad (2.45)$$

where E_k are the set of exogenous inputs that affect R_j directly and A_{ij} and A_{kj} are the impacts of auxiliary variables in the causal streams from the i th level variable and k th exogenous input, respectively. Since the exogenous inputs are known time functions or constants, if the initial values of the level variables are known, all other variables can be computed from them for that time. Then the new values of the level variables for the next point in time can then be found from the "level" equation (2.44).

DYNAMO (DYNAmic MOdels) is a computer program which compiles and executes system dynamics models. Because of the inability of a computer language to handle subscripts, DYNAMO uses a postscript notation in which .K stands for the present time t , .J stands for past time $t-dt$, and .L stands for future time $t+dt$. As in all computer programming upper case letters are used and DT is called the solution interval, the time between successive computations in the simulation. Since rate variables are assumed to be constant over DT, the double postscript is used, .JK for rates on the right side of an equation and .KL for rates on the left side. The postscript convention for system dynamics parameters is summarized in Table 2.1.

The model is executed by the computer according to the "simulation specifications" or "control statements" between the "system equations" and the "causal diagram." The first statement defines the "solution interval," DT, to be used, the length of the run, LENGTH, the plot period, PLTPER, and the print period, PRTPER. The "PLOT" statement specifies the variables to be plotted at intervals given by PLTPER and the "PRINT" statement specifies the variables that have to be printed out in a

Table 2.1

SUMMARY OF DYNAMO POSTSCRIPT CONVENTION

| TYPE OF EQUATION | TYPE OF VARIABLE | | | | | | | |
|------------------|-------------------------------|-------|------|----------------------------------|----------|---------|------------|--|
| | Dependent (Left-Hand Side) | | | Independent (Right-Hand Side) | | | | |
| | | Level | Rate | Auxiliary | Constant | Initial | Table Name | |
| L: Level | .K | .J | .JK | .J | none | none | n.p. | |
| R: Rate | .KL | .K | .JK | .K | none | none | n.p. | |
| A: Auxiliary | .K | .K | .JK | .K | none | none | none | |
| C: Constant | none | n.p.* | n.p. | n.p. | n.p. | n.p. | n.p. | |
| N: Initial | none | none | none | none | none | none | n.p. | |
| T: Table Name | none | n.p. | n.p. | n.p. | n.p. | n.p. | n.p. | |

* n.p. = not permitted

tablular form at intervals defined by PRTPER. A slash (/) between variables on the PLOT statement is to have the variables on each side of the slash plotted on different scales. Each PLOT statement produces a separate plot and each PRINT statement produces an additional line to be printed for each print period. The time axis on the plots extend down the page. The scales for each variable are specified on the other axis (the ordinate) along with the symbols used to represent the variables. If two or more characters are superimposed on the plot, the symbols appear along the side of the line opposite to the time axis [24,25].

The equations having been formulated, the next step would be to obtain an analytical solution. This is explained in the following section.

2.11 STEADY STATE ANALYSIS

The unchanging state of a system is called its "steady state". Although the given system may have an input and output, the value of the state variable does not change. An example is body temperature: it remains in a steady state even though there is continuous metabolism and heat is continually lost to the environment. It is important to note that not all the elements of a system reach the steady state at the same time. Thus, a person grows in height and weight while his body temperatures stays at 37°C.

The growth pattern of a system (or its state) usually shows two phases: transient and steady. The transient state may be regarded as a state of continual change. During the transient, all quantities that can vary are in the process of varying. The steady state represents a

condition of dynamic or static equilibrium: the state of a system does not change over time. The steady state may also be thought of as the limit of the transient state.

In the previous paragraph, reference is made to "equilibrium". Equilibrium is the equivalent to steady state. The term is used traditionally in dealing with a closed system and refers to change in the system and no interaction with the environment technically, the term steady state applies to an open system. However, when applied to system dynamics modeling for our purposes no distinction will be made.

Steady state analysis is a technique for finding the values of the variables in a system when they no longer change over time. These steady state values or equilibrium values of the variables occur when the values of the variables in question are independent of time. Given the complete mathematical description of the system in the time domain, the steady state may be found by taking the limiting values of the variables as time approaches infinity. For example, the solutions to models expressed as differential equations are often expressed in two parts: the transient and the steady state. In the limit the transient becomes zero leaving the steady state solution. Since it is a simple manner to convert the difference equations of system dynamics models to equivalent differential equations, solving these differential equations at time equals infinity affords one way of obtaining the steady state. Using Equation 2.44, the differential equation is formed as follows:

$$\lim_{t \rightarrow \infty} \frac{L_i(t) - L_i(t-1)}{dt} = \sum_{j=1}^n R_j(t-1) \quad (2.46)$$

recognizing that the left hand side defines the derivative of the level variable with respect to time and substituting Eq. 2.45 into the right hand side gives

$$\frac{dL_i(t)}{dt} = f[L_i(t)] \quad (2.47)$$

A much simpler way of obtaining the steady state solution to a system dynamics model is to work directly with the difference equations. Thus, referring again to Eq. 2.44, we are looking for the value of the levels L_i when $L_i(t) = L_i(t-1)$. The levels on each side of Eq. 2.44 are obviously equal when

$$\sum_{j=1}^n R_j(t-1) = 0 \quad (2.48)$$

Repeated substitution in Eq. 2.48 permits one to find the parameters $A_{ij}(t)$, $A_{kj}(t)$ and $L_i(t)$ from Eq. 2.45.

An example of how one moves through the system dynamics approach from verbal model to DYNAMO equations and analytical solution is presented in the next section which describes an attrition model.

2.12 ATTRITION IN A SYSTEM DYNAMICS CONTEXT

Mathematical representation of military operations have long fascinated analysts and practitioners. In 1916 English mathematician Frederick W. Lanchester represented the attrition rates of two opposing forces in the form of two differential equations, functions of the size and combat effectiveness of each side. Lanchester's model was an intellectual breakthrough in the analysis of warfare insofar as it provided deep insight into the possibilities inherent in simple models of combat. Lanchester's representation of the problem as a dynamic system is precisely the approach used in the system dynamics methodology employed in the following model [12].

The modified version of Lanchester's classical attrition model developed independently by Lotka [32] and Volterra [33] for representing the relationship between two competing species is extended to two competing forces here. Let the airpower in terms of aircraft inventory of the two forces are represented by S and X which are level variables. In a simplified manner, the basic interaction between the two forces are as follows: At any instant, the size of the S inventory is reduced at a rate proportional to both its own size and the size of the X inventory at that instant. Similarly, at any instant the reduction X inventory's size is dependent on both its own size and the size of the S inventory. More specifically, the rate of depletion of the two forces is proportional to the sizes of the two inventories and the effectiveness of the enemy force's aircrafts. The basic philosophy involved is that members of one force try to kill members of the enemy force. This is also often referred

to as the "two predator" model. It is to be observed that the system is one with a second order positive feedback that has first order negative feedback loops.

The causal diagram, the DYNAMO equations and the computer simulation output of the model are shown in Figure 2.2. The steady state analysis and the analytical approach to obtain the transient solution are presented next.

Steady State Analysis

The method described in Section 2.11, and Equation 2.48 in particular, is followed to obtain the steady state solution.

Equating the sum of the rates in Equations S-1 and X-1 of Figure 2.2 we obtain

$$ARSS_e = 0 \quad (2.49)$$

$$ARXX_e = 0 \quad (2.50)$$

Substituting in the above equations for ARSS and ARXX from Equations S-2 and X-2, of Figure 2.2, respectively we obtain

$$S_e * X_e * B = 0 \quad (2.51)$$

$$\text{and } S_e * X_e * C = 0 \quad (2.52)$$

Since both B and C are different from zero, we deduce that

$$S_e = 0 \quad \text{or} \quad X_e = 0 \quad (2.53)$$

The magnitudes of B and C along with the initial values of S and X determine which of the two, S_e or X_e is equal to zero.

* LOTKA-VOLTERRA MODEL OF ATTRITION (PREDATOR-PREDATOR)

NOTE *****
 NOTE ***** CAUSAL DIAGRAM *****
 NOTE *****

NOTE

NOTE

NOTE

NOTE

NOTE

NOTE

NOTE

NOTE

NOTE

NOTE

NOTE

NOTE *****

NOTE ***** SYSTEM EQUATIONS *****

NOTE *****

L $\dot{\$} = \text{MAX}(\dot{\$} - (DT)(AR\$\$.JK), 0)$ ($\$-1$)

N $\dot{\$} = \dot{\$}N$ ($\$-1.1$)

NOTE $\dot{\$}$ - INVENTORY OF U.S. FIGHTER AIRCRAFT (AIRCRAFT)

C $\dot{\$}N = 540$ ($\$-1.2$)

NOTE $\dot{\$}N$ - INITIAL INVENTORY OF $\dot{\$}$ (AIRCRAFT)

R $AR\$\$.KL = \dot{\$}.K * X.K * B$ ($\$-2$)

NOTE $AR\$\$.KL$ - ATTRITION RATE OF $\dot{\$}$ (AIRCRAFT PER DAY)

C $B = .004$ ($\$-3$)

NOTE B - COMBAT EFFECTIVENESS OF SOVIET FIGHTER AIRCRAFT

L $\dot{X}.K = \text{MAX}(\dot{X}.K - (DT)(ARXX.JK), 0)$ (X-1)

N $\dot{X} = \dot{X}N$ (X-1.1)

NOTE \dot{X} - INVENTORY OF SOVIET FIGHTER AIRCRAFT (AIRCRAFT)

C $\dot{X}N = 720$ (X-1.2)

NOTE $\dot{X}N$ - INITIAL INVENTORY OF \dot{X} (AIRCRAFT)

R $ARXX.KL = \dot{X}.K * X.K * C$ (X-2)

NOTE $ARXX.KL$ - ATTRITION RATE OF \dot{X} (AIRCRAFT PER DAY)

C $C = .008$ (X-3)

NOTE C - COMBAT EFFECTIVENESS OF U.S. FIGHTER AIRCRAFT

NOTE *****

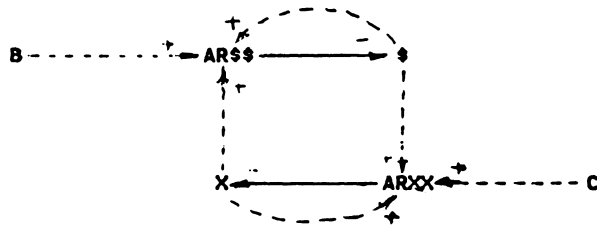
SPEC $DT = .0005 / \text{LENGTH} = 30 / \text{PLTPER} = 2 / \text{PRTPER} = 2$

PLOT $\dot{\$} = \dot{\$}, X = X$

PRINT $\dot{\$}, X, AR\$\$, ARXX$

RUN

QUIT

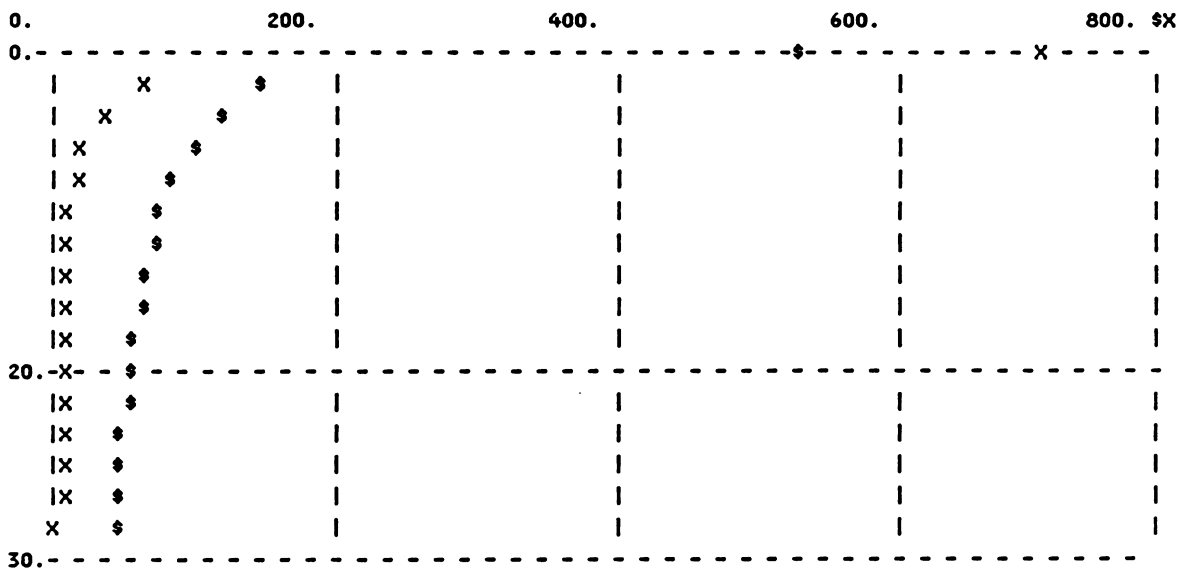


* LOTKA-VOLTERRA MODEL OF ATTRITION (PREDATOR-PREDATOR)

Fig 2.2

| | | | | | | | | | |
|-------|-------|-----|-------|----|-------|---------|-------|-------|-------|
| TIME= | .00 | \$= | 540.0 | X= | 720.0 | AR\$\$= | 1555. | ARXX= | 4147. |
| TIME= | 2.00 | \$= | 152.5 | X= | 57.5 | AR\$\$= | 35. | ARXX= | 26. |
| TIME= | 4.00 | \$= | 110.1 | X= | 29.9 | AR\$\$= | 13. | ARXX= | 7. |
| TIME= | 6.00 | \$= | 90.5 | X= | 20.2 | AR\$\$= | 7. | ARXX= | 3. |
| TIME= | 8.00 | \$= | 78.7 | X= | 15.3 | AR\$\$= | 5. | ARXX= | 2. |
| TIME= | 10.00 | \$= | 70.5 | X= | 12.3 | AR\$\$= | 3. | ARXX= | 1. |
| TIME= | 12.00 | \$= | 64.4 | X= | 10.2 | AR\$\$= | 3. | ARXX= | 1. |
| TIME= | 14.00 | \$= | 59.7 | X= | 8.8 | AR\$\$= | 2. | ARXX= | 1. |
| TIME= | 16.00 | \$= | 55.9 | X= | 7.7 | AR\$\$= | 2. | ARXX= | 0. |
| TIME= | 18.00 | \$= | 52.6 | X= | 6.8 | AR\$\$= | 1. | ARXX= | 0. |
| TIME= | 20.00 | \$= | 49.9 | X= | 6.2 | AR\$\$= | 1. | ARXX= | 0. |
| TIME= | 22.00 | \$= | 47.5 | X= | 5.6 | AR\$\$= | 1. | ARXX= | 0. |
| TIME= | 24.00 | \$= | 45.4 | X= | 5.1 | AR\$\$= | 1. | ARXX= | 0. |
| TIME= | 26.00 | \$= | 43.6 | X= | 4.7 | AR\$\$= | 1. | ARXX= | 0. |
| TIME= | 28.00 | \$= | 42.0 | X= | 4.4 | AR\$\$= | 1. | ARXX= | 0. |
| TIME= | 30.00 | \$= | 40.5 | X= | 4.1 | AR\$\$= | 1. | ARXX= | 0. |

\$=\$,X=X



Simulation Results (Fig 2.2 cont.)

Transient Solution

The transient solution can be obtained by converting the difference equations to differential equations and solving the differential equations simultaneously.

Forming the first order differential equation for S from Equation 2.51 and 2.52 we obtain

$$dS_t/dt = -ARSS_t \quad (2.54)$$

or $dS_t/dt = -B * X_t * S_t \quad (2.55)$

Similarly, the first order differential equation in X is obtained as

$$dX_t/dt = -ARXX_t \quad (2.56)$$

or $dX_t/dt = -C * X_t * S_t \quad (2.57)$

Equations 2.55 and 2.57 together form the famous Lotka-Volterra system of equations.

't' can be eliminated from the above set of equations by dividing equation 2.55 by equation 2.57 to yield

$$dS_t/dX_t = B/C \quad (2.58)$$

Rearranging the terms,

$$CdS_t = BdX_t \quad (2.59)$$

Integrating with the limits from 0 to t,

$$C(\$_t - \$_0) = B(X_t - X_0) \quad (2.60)$$

solving for X_t we obtain,

$$X_t = X_0 + (\$_t - \$_0)C/B \quad (2.61)$$

substituting in equation 2.55 for X_t we have,

$$d\$_t/dt = -B * \$_t * [X_0 + (\$_t - \$_0)C/B] \quad (2.62)$$

Separating variables in the above equation gives

$$d\$_t/[\$_t(BX_0 + C\$_t - C\$_0)] = -dt \quad (2.63)$$

for simplifying the computations let

$$(BX_0 - C\$_0)/C = U \quad (2.64)$$

Thus equation 2.63 can be rewritten as

$$d\$_t/[\$_t(\$_t - U)] = -Cdt \quad (2.65)$$

Converting the left hand side of the above equation to partial fractions yields

$$\left\{ \frac{1}{U} \left(\frac{1}{\$_t} - \frac{1}{U+\$_t} \right) \right\} d\$_t = -Cdt \quad (2.66)$$

which can be rewritten as

$$\frac{d\$_t}{\$_t} - \frac{d\$_t}{U+\$_t} = -UCdt \quad (2.67)$$

integrating with limits from 0 to t,

$$\ln [S_t/S_0] - \ln [(U+S_t)/(U+S_0)] = -UCt \quad (2.68)$$

rearranging the terms, equation 2.68 is rewritten as

$$\ln \left[\frac{\$_t / (U + \$_t)}{\$_0 / (U + \$_0)} \right] = -UCt \quad (2.69)$$

Taking the base of the natural logarithm.

$$\frac{\$_t / (U + \$_t)}{\$_0 / (U + \$_0)} = e^{-UCt} \quad (2.70)$$

rearranging the terms gives

$$\frac{\$_t}{U + \$_t} = \frac{\$_0}{U + \$_0} e^{-UCt} \quad (2.71)$$

Using the algebraic property that,

$$\text{if } \frac{Nr.L}{Dr.L} = \frac{Nr.R}{Dr.R}$$

$$\text{then } \frac{Nr.L}{Dr.L - Nr.L} = \frac{Nr.R}{Dr.R - Nr.R}$$

we obtain

$$\frac{\$_t}{U + \$_t - \$_t} = \frac{\$_0}{U + \$_0 - \$_0} e^{-UCt} \quad (2.72)$$

simplifying equation 2.72 gives

$$s_t = \frac{U \$_0}{U + \$_0 - \$_0} e^{-UCt} \quad (2.73)$$

substituting in equation 2.72 for U from equation 2.64 and then simplifying we obtain

$$S_t = \frac{(BX_0 - CS_0)S_0 e^{-(BX_0 - CS_0)t}}{BX_0 - CS_0 e^{-(BX_0 - CS_0)t}} \quad (2.74)$$

Thus, equations 2.61 and 2.74 form the transient solution of the Lotka-Volterra attrition model.

3.0 THE MODEL - P.C. SURMAN

3.1 INTRODUCTION

The SURMAN (SURvivability MANagement) model has been developed to detail the essential Survivability Management parameters and their causal relationships throughout the life cycle of aircraft systems. The Model is expressed in the System Dynamics methodology. Specifically, the primary objectives of developing the model are to develop an instrumentality that can be used

- for forecasting Macro behavior
- for predicting consequences of alternative courses of action
- for conducting sensitivity analysis to establish research and data gathering priorities
- to serve as a communication vehicle among those concerned with Survivability issues.

The problem consists of two decision making orientations.

1. The Hierarchical and
2. The Chronological.

Regarding the hierarchial, there are three policy levels of defense management and national security planning:

1. The quantity of resources available to the nation, in general, and to the defense establishment, in particular
2. The allocation of these resources within the DOD by Service and by function
3. The allocation of RDT&E within the JTCG/AS

Regarding the chronological, there are identification of decision nodes throughout the combat aircraft systems life cycle -- from Research and Development to mission requirements to design to acquisition to modification to Operations and Maintenance to retirement, in the case of peacetime, and to attrition, in the case of wartime.

In consideration of this two-dimensional requirement, two responses have been formulated:

1. The Top-Down Approach - which starts at the top of the hierarchy, and
2. The Bottom-Up Approach - which starts with the subgroups in the JTCG/AS and works up the hierarchy

In the Top-Down Approach, SURMAN is comprised of five submodels with varying numbers of components within each

1. Economy
2. Budget
3. Procurement
4. Attrition and
5. Survivability

In addition to these components, the Survivability Submodel is made up of 16 Susceptibility/Vulnerability subsystems for performing Susceptibility/Vulnerability assessments.

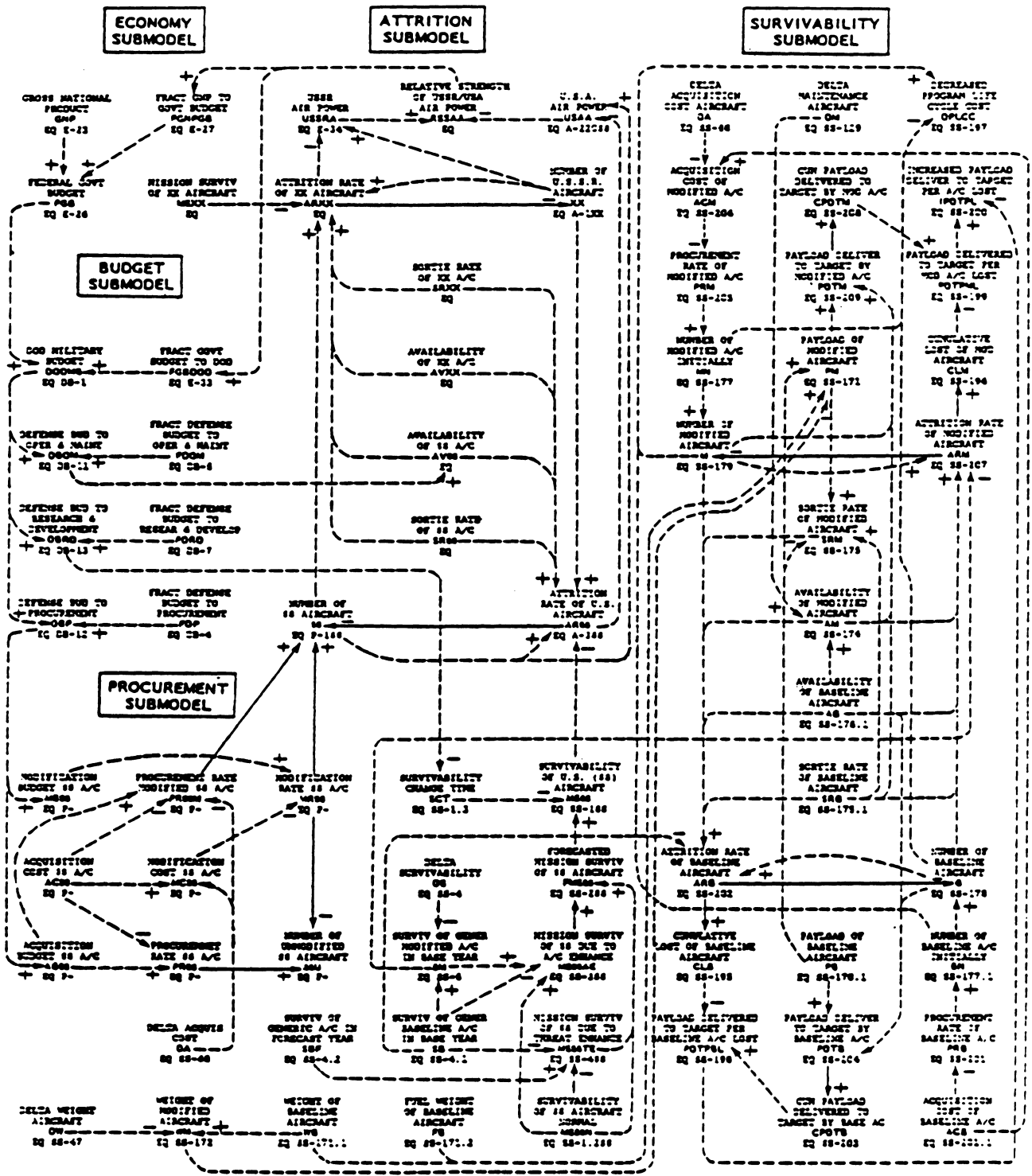
As stated earlier in Chapter 1, SURMAN is significant in distinguishing between the "inputs" and the "outputs". In the present context, the inputs are the decision parameters and the outputs are the indicators or measures of effectiveness.

The SURMAN, as such, is therefore a large scale model. The P.C.SURMAN, which has been developed here encapsulates the SURMAN, making it compact and more accessible. The P.C.SURMAN has a structure essentially similar to the SURMAN. However, the Economy Submodel and the Budget Submodel have been combined together into one submodel. Figure 3.1 shows the causal relationships between the principal parameters involved in the model. Table 3.1 shows the scenario analysis of the P.C.SURMAN. Each of the submodels of the P.C. SURMAN is explained in the following sections.

3.2 ECONOMY/BUDGET SUBMODEL

3.2.1 U.S. ECONOMY SUBMODEL

The quantity of national resources available is the highest level in the decision hierarchy. The national economy determines the quantity of natural resources available. The economy is indeed linked to the industrial capital and the industrial output.



Structure of the PC SURMAN
Fig. 3.1

Table 3.1

JTCG SURMAN MODEL - PC VERSION
SCENARIO ANALYSES

| <u>DECISION HIERARCHY</u> | <u>SUBMODEL</u> | <u>DECISION PARAMETERS (INPUTS)</u> | <u>INDICATORS (OUTPUTS)</u> |
|---------------------------|--|--|--|
| 1 | ECONOMY | FGBDDT-FRACT GOVT BUDGET TO DOD | COMVR-COMBAT VALUE RATIO |
| 2 | BUDGET | FDP-FRACT DOD BUDGET TO PROCUREMENT | \$\$-NO. OF COMBAT AIRCRAFT |
| 3A | SURVIVABILITY (TRADE-OFF ANALYSIS) | SB-SURVIV. OF BASELINE AIRCRAFT DS-DELTA SURVIVABILITY DW-DELTA WEIGHT DA-DELTA ACQUISITION COST DM-DELTA MAINTENANCE COST | IPDTPL-INC. PAYLOAD DEL. TARGET PER LOSS DPLCC-DEC. PROGRAM LIFE CYCLE COST COMVR-COMBAT VALUE RATIO MS\$\$-SURVIVABILITY OF \$\$ |
| 3B | SURVIVABILITY (THREAT ENHANCEMENT) | SB-SURVIV. OF BASELINE AIRCRAFT SUSCE-SUSC. OF \$\$ TO ENHANCED THREAT VULNE-VULN. OF \$\$ TO ENHANCED THREAT | COMVR-COMBAT VALUE RATIO MS\$\$-SURVIVABILITY OF \$\$ |

The Gross National Product (GNP) is an indicator of the economic condition prevailing in a country. It will, therefore, be an appropriate parameter that could be used. Gross National Product is the summation of all industry products of the nation, industry product being the difference between the industry output and industry usage.

The inflation rate is also accounted for in the model to show the growth of the economy in both constant 1980 dollars and in inflated dollars [26]. The value of inflationary growth rate was calculated as an average inflationary growth rate from 1972 to 1980 and it was assumed to be constant over the simulation period. The Inflation Multiplier is used to choose between the constant dollars and the inflated dollars. The inflation multiplier takes on value of 0, if GNP in constant dollars is desired and 1 if GNP inflated dollars is to be used.

The Federal Government Budget (FGB), which is a fraction of the GNP, is directly influenced by the value of the U.S.S.R. military power to the U.S. military power expressed as the Combat Value Ratio Recognized (COMVRR), during the peacetime. During the wartime, the Federal Government Budget is a constant and higher fraction of the GNP. The table function GNPGBT, fraction of GNP to Government Budget, is used to relate COMVRR to FGB. The Department of Defense Military Budget, which is a fraction of the FGB, is again directly influenced by the ratio of the military powers of the U.S.S.R. and the U.S.A. The decision parameter at this level is the "Fraction of the Government Budget to DOD" which when multiplied by FGB gives the DOD Military Budget. The indicator here is the Combat Value Ratio recognized and it is used in the TABHL function FGBDDT to relate to FGBDOD.

3.2.2 U.S. DEFENSE BUDGET SUBMODEL

Having dealt with the highest level of hierarchy in the previous section, this section deals with the next level -- in the hierarchy of defense economics -- namely the allocation of resources within the D.O.D. by service and by function. Here the questions of proportion of these resources allocated to national security are addressed.

Problems at this level are primarily internal problems of the defense departments and agencies. DOD military Budget is proportioned amongst the three major activities of Operations and Maintenance (DBOM), Procurement (DBP), and Research and Development (DBRD). The allocation of DOD military budget to each of the three activities is performed using the variables corresponding to the appropriate fractions of the Defense Budget, viz., FDOM, FDP, and FDRD. TABLE functions are used to depict the variations, if any, of these fractions with time.

3.3 PROCUREMENT SUBMODEL

Military decisions may be classified by kind as well as level. It is useful to distinguish: operations decisions (strategy and tactics), procurement of force composition decisions, and research and development decisions. The basic difference among these kinds of decisions, from the point of view of analysis, is the time at which the decision affects the capability of the military forces concerned. An operations decision can affect capability almost immediately. A decision to procure something, on the other hand, cannot affect capability until the thing procured is

produced and fitted into operational forces. Finally, decisions to develop something based on researching it tend to affect capabilities at an even later date -- after the system has been developed, procured and fitted into operational forces. This section describes the submodel pertaining to the procurement function of military combat aircraft.

The acquisition of a new aircraft or modification of an older version of the same aircraft leads to an increase in the inventory of each type of aircraft. The unmodified, or older, version's inventory is depleted by retirement, modification to the improved versions, and attrition. Operational errors, aircraft malfunctions, bad weather, and natural disasters are responsible for the attrition during peacetime. However, during wartime the attrition process is more complicated and is treated separately in the attrition submodel. Similarly, the inventory of the modified aircraft is increased by the procurement of new modified aircraft, and the modification of the older versions, while attrition of the modified aircraft depletes its inventory. The modified aircrafts are not retired during the study period. The aircraft that have been retired from active service are utilized by continental defense by the Coast Guard and thus add to its inventory. Both the acquisition and modification rates depend directly on the acquisition and modification budgets and inversely on the acquisition and modification costs.

The Procurement Budget is obtained as the output of the Budget Submodel and from this budget the acquisition and modification budgets are apportioned. Having treated budgets for acquisition and modification of aircraft, the costs remain to be considered. The lower casualty rate and a more efficient military, resulting from the technological progress

has not come cheaply. The U.S. tactical air power is perhaps the purest example of this trade-off. The extent of the problem is easily illustrated. During the peak procurement year of World War II (1943) the Army Air Corps Committed \$2.5 billion to purchase tactical aircraft: fighter and light and medium bombers of a dozen popular types. For fiscal year 1975 the Air Force requested \$1.1 billion to buy modern airplanes for the same tactical purposes. The difference is that in 1943 the Air Corps got 25,000 planes for its money; in 1975 the Air Force got 100. The average cost of a tactical warplane procured increased from \$100,000 in 1943 to \$11,000,000 in 1975 [28]. Recent comparisons are no more heartening. Cost data on the 55 major weapons systems being produced by DOD in 1980 showed them to be 45% higher than the original estimate. New tactical fighters for the Air Force and Navy will run from a low of about \$11 million per plane for the F-16 to a high of about \$24 million per unit for the F-14A. Even the Navy's "low cost" fighter, the F/A-18, will cost over \$17 million a piece.

In this model, the acquisition cost of the aircraft is assumed to be affected by two multipliers: the acquisition cost inflationary multiplier, and the acquisition cost procurement multiplier. The former adjusts the acquisition cost to inflationary growth, and the latter multiplier adjusts the acquisition cost to non-inflationary growth. The non-inflationary increase is attributable to three factors: maximum technological substitution, obsolescence, and procurement stretch-out [29].

The modification cost of each aircraft is the cost of modifying an older version of that aircraft and bringing it to an operational level

similar to the ones that are presently procured. The value of modification cost for is determined by multiplying the acquisition cost by Delta acquisition cost. The Delta change in acquisition cost is the percentage change in costs associated with susceptibility and vulnerability reduction techniques of an aircraft and it is one of the inputs into the survivability submodel.

3.4 ATTRITION SUBMODEL

The attrition submodel is used to describe and to quantify the survivability of combat aircraft in encounters with hostile forces. Military Standards and Military Handbooks identify numerous descriptors and summary measures used to define the results of engagements between aircraft and various threats [5, 6]. In general, these measures address the probability of survival per shot from a given weapon, probability of survival per encounter with a given weapon, and probability of survival per sortie or mission during which an aircraft may have multiple engagements with the various weapons of a zone defense. Aircraft probability of survival is a summary measure that an aircraft will survive a defined level of damage or kill category -- attrition, forced landing, mission abort, and mission available. In the model the kill category used is attrition kill, which covers those aircraft with combat damage so extensive that it is neither reasonable nor economical to repair [10].

The number of U.S. combat aircraft is reduced by the increase in the cumulative losses of the aircraft. The cumulative losses of the aircraft is increased by attrition of the aircraft. The attrition rate of the

aircraft during peacetime is different from that during wartime, as mentioned in the previous section. Wartime attrition rate is the product of the number of aircraft available, the sortie rate and the probability of not surviving a mission.

In this model, the sorties are divided into three types, sortie versus sea targets, land targets and airborne targets (enemy aircraft). The sortie rate varies directly with the availability of the aircraft (probability), fraction sortie versus a certain target (fraction), sortie rate maximum (sorties/day) and the probability of encounter (probability) between aircraft or between aircraft and land or sea threats. There is also a maximum sortie rate determined by the crew to aircraft ratio and this relationship is captured in a table function.

The mission survivabilities of the U.S. aircraft for each of the three roles is expressed in terms of the overall mission survivability of the entire fleet. A multiplier is used in each case based on the overall strike capabilities for sorties against land and sea targets and the mission survivability versus airborne targets obtained based on the mathematical formulation discussed in Section 2.4.

3.5 AVAILABILITY COMPONENT

Operational availability is an index of weapon system material readiness, including system software where applicable, in a mission environment [30]. It does not attempt to capture personnel readiness nor the probability of mission success. It is instead of a measure of the probability of an item, assembly or system being in a condition, generally

referred to as "up", such that it can perform its intended function, within acceptable limits of degradation, when called upon. This section addresses the military combat aircraft availability phenomenon.

In general, the availability of combat aircraft is a function of supply and demand -- the supply or capacity of maintenance/repair facilities based on aircraft maintainability and the demand (arrival rates) requiring these services based on aircraft reliability.

The availability of U.S. aircraft depends upon the number of aircraft requiring maintenance and repair and the time spent to get them ready for combat. The principal parameters affecting availability are, therefore, the maintenance and repair times and the frequency at which maintenance and repair are required.

The nature of the work done in maintenance is primarily visual inspection, operational checkout, minor servicing, external adjustments, removal and replacement of some components, etc. Therefore, it is expected that the frequency of demand for such services to be high and the time required to complete these services to be relatively short. Obviously, the availability of combat aircraft can be enhanced by reducing the aircraft mean maintenance down time. This can be accomplished by allocating more operations and maintenance budget to such services.

"Failure" of an aircraft results in it being taken for repair, which is more elaborate. The nature of the repair work includes detailed inspection and system checkouts, major servicing, major equipment repair and modifications, complicated adjustments, limited calibration and overload from the primary maintenance. As in the case of maintenance, the availability of U.S. combat aircraft can be enhanced by reducing the

aircraft's mean time to repair. This can be achieved by allocating more of the DOD budget to operations and maintenance, and more of the Operations and Maintenance budget to such activities. The availability can also be enhanced by increasing the mean time between maintenance and the mean time between failure. This can again be accomplished by allocating more of the DOD budget to research and development.

3.6 SURVIVABILITY SUBMODEL

The design and operation of air weapons based on consideration given to survivability is a relatively new philosophy for waging war. As late as World War II, it made sense, in time and dollars, to simply boost production and training inputs to resolve problems created by attrition. Most advances in survivability that occurred in World War II and the post World War II era were either "crew pacifiers" or unintended side-effects from efforts directed to other ends -- increased strength, performance, load carrying capacity, reliability, etc. [31].

While humanitarian awareness must be acknowledged, the thrust for emphasis on aircraft survivability has come about mainly for a number of cost-sensitive reasons. At any rate, survivability has become a self-reinforcing trend, encouraged because of the higher costs of hardware, and by the higher maintenance and training costs which have resulted both from economic conditions and evolutionary advances in equipment and tactics. There are secondary and tertiary effects: an increased product value must serve longer, the longer life requires a broader support base, and the broader support base requires a higher

investment in spares, facilities, and support equipment. At the same time, increases in weapons capability and complexity increase the level of skill required of flight crews; greater skill and training in the cockpits justifies survivability enhancement to protect more expensive personnel assets [10].

In this section, organized around aircraft survivability, we try to integrate the benefits and penalties associated with aircraft survivability enhancement techniques that are recommended in Military Handbook, MIL-HDBK-336 [6]. The benefits can be measured in terms of increased probability of survival, reduced force requirements, reduced attrition, etc. The penalties can be measured in terms of increased weight, reduced payload, reduced performance, increased cost, etc.

In the model the mission survivability of the U.S. combat aircraft is shown to be a function of the forecasted mission survivability of the aircraft and a time adjustment factor. The "survivability change time", which is the time adjustment factor, adjusts the mission survivability over time, 20 years in the simulation period adopted. The forecasted mission survivability depends directly on the initial mission survivability, the change of mission survivability due to aircraft enhancement, and the change of mission survivability due to threat enhancement. The change in mission survivability of an aircraft due to aircraft enhancement is directly dependent on the difference between the survivability of a generic modified aircraft in the base year and the survivability of a generic baseline aircraft in the base year. Similarly, the change in survivability of an aircraft due to threat enhancement depends directly on the difference in survivability of the generic

baseline aircraft in the forecast year and the survivability of the generic baseline aircraft in the base year. The survivability of the generic modified aircraft in the base year depends on the survivability of the generic baseline aircraft in the base year, and on the change in survivability of generic aircraft due to enhancement. The survivability of the generic baseline aircraft in the forecast year depends on the susceptibility of the aircraft due to enhanced threat and its vulnerability (enhanced weighted probability of kill given a hit), as discussed in equation 2.1.

Besides the change in survivability, there are changes in other parameters influencing the performance of the aircraft, and are represented by "deltas" and are delta weight of generic aircraft, delta acquisition cost of generic aircraft, and delta maintenance cost of generic aircraft. Each delta is determined by subtracting the modified value of the parameter from its base value and dividing the results by the base value.

The delta acquisition cost influences the acquisition cost of generic modified aircraft. The acquisition cost of generic modified aircraft also depends on the acquisition cost of generic baseline aircraft. A higher acquisition cost reduces the procurement rate of the generic modified aircraft which in turn reduces the inventory of generic modified aircraft during peacetime buildup. The inventory of modified aircraft at the end of peacetime buildup period is the initial number of modified aircraft for the wartime. The initial number of generic baseline aircraft is determined in a similar manner except that the acquisition cost of generic baseline aircraft is not influenced by delta acquisition cost. The number

of generic modified and generic baseline aircraft not only influence each other in a positive feedback loop, but also do they both influence the decreased program life cycle cost. The decreased program life cycle cost is a figure of merit that can be used to trade-off the initial force size of modified and baseline aircraft for the wartime.

Another figure of merit or measure of effectiveness that can be used for trading-off the modified and baseline aircraft survivability parameters is the increased payload delivered to target per aircraft lost. This measure of effectiveness is calculated by subtracting the cumulative payload delivered to target per baseline aircraft lost from the cumulative payload delivered to target per modified aircraft lost and dividing the results by cumulative payload delivered to target per modified aircraft lost. The cumulative payload delivered to target per baseline aircraft lost is simply the cumulative payload delivered to target by baseline aircraft. The cumulative loss of baseline aircraft is a level variable that depends only on the attrition rate of baseline aircraft. The cumulative payload delivered to target by baseline aircraft is also a level variable that depends on the payload delivered to target by baseline aircraft. Payload delivered to target by baseline aircraft is a function of payload carried by baseline aircraft, number of baseline aircraft, availability of baseline aircraft, and sortie rate of baseline aircraft. Similarly, the cumulative payload delivered to target per modified aircraft lost is cumulative payload delivered to target by modified aircraft divided by cumulative loss of modified aircraft. The cumulative loss of modified aircraft is a level variable and depends only on the attrition rate of modified aircraft. The cumulative payload delivered

to target by modified aircraft is also a level variable and depends on the amount of payload delivered to target by modified aircraft. The amount of payload delivered to target by modified aircraft depends on payload carried by modified aircraft, number of modified aircraft, availability of modified aircraft, and sortie rate of modified aircraft. However, the availability of modified aircraft is a function of the availability of baseline aircraft and it is influenced directly by delta maintenance cost of generic aircraft. The sortie rate of modified aircraft is a function of the sortie rate of baseline aircraft, payload of baseline aircraft, and payload of modified aircraft. The payload carried by modified aircraft is a function of payload carried by baseline aircraft, fuel weight of baseline aircraft, empty weight of baseline aircraft, and the empty weight of modified aircraft. The empty weight of modified aircraft is a function of empty weight of baseline aircraft and is influenced by delta weight of generic aircraft. It is obvious that an increase in empty weight of modified aircraft due to survivability enhancement would decrease the payload carrying capacity of the aircraft.

The control parameters "ROTOR", "FIXED" and "VTOL" are used to indicate the type of aircraft under consideration. "ROTOR" is used for rotary wing, "FIXED" for fixed wing and "VTOL" for the vertical take-off and landing type of aircraft.

Some of the other indicators, or measures of effectiveness, used are "cumulative targets destroyed per aircraft lost", "combat value ratio", and "kill per aircraft lost". Cumulative targets destroyed per aircraft lost is used to measure the effectiveness of attack and bomber aircraft, since their operations are primarily destroying the enemy's land targets.

Cumulative targets destroyed is influenced by the sortie rate of the aircraft versus land targets, the number of aircraft, and the targets destroyed per sortie of the aircraft. The cumulative losses of the aircraft is obtained from the attrition submodel and the cumulative targets destroyed per aircraft lost is determined as the quotient of the cumulative targets destroyed divided by the cumulative aircraft lost. The mission is more effective if the value of targets destroyed per aircraft lost is higher, which means that more aircraft survive or more targets are destroyed.

Combat value ratio is a measure of effectiveness based on the condition in which the two sides forces are equal. Essentially combat value ratio is a ratio of the effective fighting strengths of two forces, which in the present case is the ratio of the fighting strength of the U.S. and that of the U.S.S.R. In the simplest manner this relationship can be expressed in terms of the initial numerical strengths of the forces and their effectiveness against one another. A combat value ratio of 1.0 indicates that no side is gaining over the other. A combat value ratio greater than 1.0 indicates that the U.S. side is gaining over the U.S.S.R. In the model, a true factor is also invoked in the form of time to recognize relative air combat effectiveness. The simulation is started with a combat value ratio recognized of unity. This is then adjusted over the simulation period using the combat value ratio and the time to recognize relative air combat effectiveness. The air combat effectiveness is influenced by the sortie rate of the aircraft against the enemy force and the survivability of the aircraft on such a mission.

Kills per aircraft lost are basically used to measure the effectiveness of fighter aircraft which engage enemy aircraft in an air combat and kill the enemy's aircraft in their missions. Kills per aircraft lost is obtained by dividing the cumulative losses of the enemy aircraft by the cumulative losses of our own aircraft. The higher the value of kills per aircraft lost, the better the fighter aircraft in their mission.

In the model developed, some of the measures of effectiveness in the attrition component of the survivability model have been computed using the analytical solution. This is to determine if the modified aircraft is better than the baseline aircraft. The attrition model used is described in section 4.2 and the analytical solution is derived in Appendix A.

The computer program developed for the P.C.SURMAN is presented in the next section.

3.7 COMPUTER PROGRAM OF P.C.SURMAN

The DYNAMO equations used for the simulation in the P.C.SURMAN have been developed based on the methodology described in Chapter 2. For convenience and ease of understanding, the model is broken down into submodels as has been discussed in the previous sections of this chapter. The equations in the DYNAMO language are shown in Figure 3.2 . The results of the simulation are then discussed following the model.

```

* JTCG/AS SURMAN MODEL - (GENERIC VERSION OF TOP-DOWN SEGMENT)
NOTE *****
NOTE ***** U.S. DEFENSE BUDGET SUBMODEL *****
NOTE *****
A GNP.K=CLIP(GNPIID.K,GNPICD.K,INFLM,0) (DB-1)
NOTE GNP-GROSS NATIONAL PRODUCT ($/YR)
A GNPIID.K=TABHL(GNPIIDT,TIME.K,1980,2000,1) (DB-1.1)
T GNPIIDT=2.77E12/2.90E12/3.11E12/3.34E12/3.59E12/3.86E12/4.16E12/
X 4.48E12/4.83E12/5.21E12/5.62E12/6.05E12/6.52E12/7.02E12/7.56E12/
X 8.13E12/8.73E12/9.38E12/10.07E12/10.80E12/11.55E12
NOTE GNPIID-GROSS NATIONAL PRODUCT IN INFLATED DOLLARS ($/YR)
A GNPICD.K=TABHL(GNPICDT,TIME.K,1980,2000,1) (DB-1.2)
T GNPICDT=2.68E12/2.76E12/2.84E12/2.93E12/3.02E12/3.11E12/3.20E12/
X 3.29E12/3.38E12/3.48E12/3.58E12/3.68E12/3.78E12/3.89E12/3.99E12/
X 4.10E12/4.21E12/4.33E12/4.45E12/4.57E12/4.69E12
NOTE GNPICD-GROSS NATIONAL PRODUCT IN CONSTANT 1980 DOLLARS ($/YR)
C INFLM=1 (DB-1.3)
NOTE INFLM-INFLATION MULTIPLIER (DIM)
A FGB.K=GNP.K*FGNPGB.K (DB-2)
NOTE FGB-FEDERAL GOVERNMENT BUDGET ($/YR)
A FGNPGB.K=CLIP(FGNPGW,(TABHL(GNPGBT,COMVRR.K,0,2,.5)),
X TIME.K,WAR) (DB-3)
T GNPGBT=.20/.21/.22/.23/.24 (DB-3.1)
NOTE FGNPGB-FRACT GNP TO GOVERNMENT BUDGET (DIM)
C FGNPGW=.25 (DB-3.2)
NOTE FGNPGW-FRACT GNP TO GOVERNMENT BUDGET DURING WARTIME (DIM)
A DODMB.K=FGB.K*FGBDOD.K (DB-4)
NOTE DODMB-DOD MILITARY BUDGET($/YR)
A FGBDOD.K=CLIP(FGBDDW,(TABHL(FGBDDT,COMVRR.K,0,2,.5)),
X TIME.K,WAR) (DB-5)
T FGBDDT=.235/.24/.25/.27/.30 (DB-5.1)
NOTE FGBDOD-FRACT GOVERNMENT BUDGET TO DEFENSE (DIM)
C FGBDDW=.35 (DB-5.2)
NOTE FGBDDW-FRACT GOVERNMENT BUDGET TO DEFENSE DURING WARTIME (DIM)
A FDOM.K=TABHL(FDOMT,TIME.K,1980,2000,5) (DB-6)
T FDOMT=.34/.31/.33/.34/.34 (DB-6.1)
NOTE FDOM-FRACT DEFENSE BUDGET TO OPERATIONS & MAINTENANCE (DIM)
A FDP.K=TABHL(FDPT,TIME.K,1980,2000,5) (DB-7)
T FDPT=.22/.24/.24/.24/.24 (DB-7.1)
NOTE FDP-FRACT DEFENSE BUDGET TO PROCUREMENT (DIM)
A FDRD.K=TABHL(FDRDT,TIME.K,1980,2000,5) (DB-8)
T FDRDT=.10/.10/.10/.10/.10 (DB-8.1)
NOTE FDRD-FRTACT DEFENSE BUDGET TO RESEARCH & DEVELOPMENT (DIM)
A DBOM.K=FDOM.K*DODMB.K (DB-9)
NOTE DBOM-DEFENSE BUDGET TO OPERATIONS & MAINTENANCE (DIM)
A DBP.K=FDP.K*DODMB.K (DB-10)
NOTE DBP-DEFENSE BUDGET TO PROCUREMENT ($/YR)
A DBRD.K=FDRD.K*DODMB.K (DB-11)
NOTE DBRD-DEFENSE BUDGET TO RESEARCH AND DEVELOPMENT ($/YR)

```

Fig 3.2

```

C   WAR=2000
N   TIME=1980
NOTE *****
NOTE ***** PROCUREMENT SUBMODEL *****
NOTE *****
L   $$U.K=MAX(0,$$U.J+(DT)(PR$$U.JK-AR$$U.JK-MR$$U.JK-RR$$U.JK)) (P-1)
N   $$U=$$UN (P-1.1)
NOTE $$U-UNMODIFIED U.S. COMBAT AIRCRAFT (AIRCRAFT)
C   $$UN=13000 (P-1.2)
NOTE $$UN-UNMODIFIED U.S. COMBAT AIRCRAFT INITIALLY (AIRCRAFT)
R   PR$$U.KL=CLIP(0,AB$$K/(AC$$K*CLIP(360,1,TIME.K,WAR)),TIME.K,1990)
NOTE (P-2)
NOTE PR$$U-PROCUREMENT RATE OF UNMODIFIED U.S. COMBAT AIRCRAFT (AC/YR)
R   MR$$U.KL=MIN(MB$$K/(MC$$K*CLIP(360,1,TIME.K,WAR)),$$U.K) (P-3)
NOTE MR$$U-MODIFICATION RATE OF UNMODIFIED U.S. AIRCRAFT (AIRCRAFT/YR)
R   RR$$U.KL=MAX(0,PR$$JK) (P-4)
NOTE RR$$U-RETIREMENT RATE OF UNMODIFIED U.S. COMBAT AIRCRAFT (AC/YR)
R   AR$$U.KL=CLIP($$U.K*NPA,$$U.K*NWA,WAR,TIME.K) (P-5)
NOTE AR$$U-ATTRITION RATE OF UNMODIFIED U.S. COMBAT AIRCRAFT (AC/YR)
C   NPA=.01 (P-6)
NOTE NPA-NORMAL PEACETIME ATTRITION (AIRCRAFT/YR)
C   NWA=.2 (P-7)
NOTE NWA-NORMAL WARTIME ATTRITION (AIRCRAFT/YR)
A   AB$$K=DBP.K*FPBAA.K (P-8)
NOTE AB$$-ACQUISITION BUDGET OF U.S. COMBAT AIRCRAFT ($/YR)
A   FPBAA.K=TABHL(FPBAAT,TIME.K,1980,2000,2) (P-9)
T   FPBAAT=.10/.10/.10/.10/.10/.10/.10/.10/.10/.10 (P-9.1)
NOTE FPBAA-FRACT PROCUREMENT BUDGET TO A/C ACQUISITION (DIM)
A   AC$$K=AC$$N*ACIM.K*ACLM.K (P-10)
NOTE AC$$-ACQUISITION COST OF U.S. COMBAT AIRCRAFT ($/AIRCRAFT)
C   AC$$N=30E6 (P-10.1)
NOTE AC$$N-ACQUISITION COST OF U.S. COMBAT AIRCRAFT NORMAL ($/AIRCRAFT)
A   ACIM.K=CLIP(ACIMT.K,1,INFLM,0) (P-11)
A   ACIMT.K=TABHL(ACIMTT,TIME.K,1980,2000,1)
T   ACIMTT=1.00/1.046/1.093/1.142/1.191/1.241/1.291/1.343/1.396/
X   1.450/1.504/1.560/1.615/1.671/1.726/1.782/1.837/1.893/
X   1.948/2.004/2.059
NOTE ACIM-ACQUISITION COST INFLATIONARY MULTIPLIER (DIM)
A   ACLM.K=TABLE(ACLMT,DODMPR.K/DODBR.K,0,5,1) (P-12)
T   ACLMT=.5/1/1.4/1.7/1.9/2 (P-12.1)
NOTE ACLM-ACQUISITION CYCLE LENGTH MULTIPLIER (DIM)
A   DODMPR.K=TABHL(DODMPRT,TIME.K,1980,2000,5) (P-12.2)
T   DODMPRT=1/1.1/1.2/1.3/1.4 (P-12.3)
NOTE DODMPR-DOD MAJOR PROGRAM RATIO (DIM)
A   DODBR.K=FGBDOD.K/FGBDN (P-12.4)
NOTE DODBR-DOD BUDGET RATIO (DIM)
C   FGBDN=.2
NOTE FGBDN - FRACT GOVT BUDGET TO DEFENSE NORMAL (DIM)
A   MBSS.K=FPBAM.K*DBP.K (P-13)
NOTE MBSS-MODIFICATION BUDGET U.S. COMBAT AIRCRAFT ($/YR)
A   FPBAM.K=TABHL(FPBAMT,TIME.K,1980,1990,2) (P-14)

```

Fig. 3.2 (Cont.)

T FPBANT=.2/.2/.2/.2/.2/.2
NOTE FPBANT-FRACT PROCUREMENT BUDGET TO AIRCRAFT MODIFICATION(DIM)
A MC\$\$.K=-AC\$\$.K*DA.K (P-15)
NOTE MC\$\$-MODIFICATION COST OF U.S. AIRCRAFT (\$/AIRCRAFT)
A \$\$.K=\$\$U.K+\$\$M.K (P-16)
NOTE \$\$-TOTAL NO. OF MODIF. & UNMODIF. U.S. COMBAT AIRCRAFT (AIRCRAFT)
L \$\$M.K=MAX(0,\$\$M.J+(DT)(PR\$\$.JK+MR\$\$U.JK-AR\$\$.JK-RR\$\$.JK)) (P-17)
N \$\$M=\$\$MN (P-17.1)
NOTE \$\$M-MODIFIED U.S.COMBAT AIRCRAFT (AIRCRAFT)
N \$\$MN=0 (P-17.2)
NOTE \$\$MN-MODIFIED U.S. COMBAT AIRCRAFT INITIALLY (AIRCRAFT)
C O=.01
NOTE O - ZERO
R PR\$\$.KL=CLIP(AB\$\$.K/(AC\$\$.K*(1-DA.K)*CLIP(360,1,TIME.K,WAR)),0
X ,TIME.K,1990)
NOTE PR\$\$-PROCUREMENT RATE OF MODIFIED U.S. AIRCRAFT (AIRCRAFT/YR)
R RR\$\$.KL=0 (P-19)
NOTE RR\$\$-RETIREMENT RATE OF MODIFIED U.S. AIRCRAFT (AIRCRAFT/YR)
R AR\$\$.KL=CLIP(\$\$M.K*NPA,WAR\$\$.JK,WAR,TIME.K) (P-20)
NOTE AR\$\$-ATTRITION RATE OF MODIFIED U.S. AIRCRAFT (AIRCRAFT/YR)
L \$\$CAD.K=\$\$CAD.J+(DT)(RR\$\$U.JK+RR\$\$.JK)
N \$\$CAD=\$\$CADN
C \$\$CADN=4000
NOTE \$\$CAD-U.S. COMBAT A/C IN CONTINENTAL AIR DEFENSE (COAST GUARD) (A/C)
NOTE *****
NOTE ***** ATTRITION SUBMODEL *****
NOTE *****
R WAR\$\$.KL=CLIP(\$\$.K*SR\$\$ST.K*(1-MS\$\$ST.K)+\$\$.K*SR\$\$LT.K*(1-MS\$\$LT.K)
X XX.K*SRXX\$\$.K*(1-MS\$\$XX.K),NPA*\$\$.K,TIME.K,WAR) (A-3\$)
NOTE WAR\$\$-WARTIME ATTRITION RATE U.S. COMBAT AIRCRAFT(AIRCRAFT/DAY)
L CL\$\$.K=CL\$\$.J+(DT)(AR\$\$.JK) (A-4\$)
N CL\$\$=0 (A-4.1\$)
NOTE CL\$\$-CUMULATIVE LOSSES OF U.S. COMBAT AIRCRAFT(AIRCRAFT)
A SR\$\$ST.K=FS\$\$ST*MIN(AA\$\$ST/(1-MS\$\$ST.K),SR\$\$MX.K*AV\$\$.K) (A-6\$)
NOTE SR\$\$ST-SORTIE RATE U.S. COMBAT A/C VS SEA TARGETS(NUMBER PER DAY)
A SR\$\$MX.K=TABLE(SR\$\$MT,USCR.K,0,2,.4) (A-6.1\$)
T SR\$\$MT=0/1.8/3/4/4.8/5 (A-6.2\$)
NOTE SR\$\$MX-SORTIE RATE MAXIMUM FOR U.S. COMBAT AIRCRAFT (NUMBER PER DAY)
C FS\$\$ST=.2 (A-6.3\$)
NOTE FS\$\$ST-FRACT U.S. AIRCRAFT SORTIES VS SEA TARGETS (DIM)
C AA\$\$ST=.02 (A-6.4\$)
NOTE AA\$\$ST-ALLOWABLE ATTRITION VS SEA THREATS (AIRCRAFT/DAY)
A USCR.K=1.0 (A-6.5\$)
NOTE USCR-U.S. CREW RATIO (CREWS/AIRCRAFT)
A MS\$\$ST.K=MS\$\$.K*\$\$\$STM (A-7\$)
NOTE MS\$\$ST-MISSION SURVIVABILITY \$\$ VS SEA THREATS (PROB)
C \$\$\$STM=.98 (A-7.1\$)
NOTE \$\$\$STM-SURVIVABILITY \$\$ VS SEA THREATS MULT (DIM)(FROM VULN. AREAS)
A SR\$\$LT.K=FS\$\$LT*MIN(AA\$\$LT/(1-M\$\$LT.K),SR\$\$MX.K*AV\$\$.K) (A-23\$)
NOTE SR\$\$LT-SORTIE RATE \$\$ VS LAND TARGETS (NUMBER PER DAY)
C FS\$\$LT=.4 (A-23.1\$)

Fig. 3.2 (Cont.)

NOTE FSS\$LT-FRACT U.S. AIRCRAFT SORTIES VS LAND TARGETS (DIM)
C AA\$LT=.02 (A-23.2\$)
NOTE AA\$LT-ALLOWABLE ATTRITION VS LAND THREATS (AIRCRAFT/DAY)
A MS\$LT.K=MS\$.K*S\$LTM (A-24\$)
NOTE MS\$LT-MISSION SURVIVABILITY \$\$ VS LAND THREATS (PROB)
C S\$LTM=.99 (A-24.1\$)
NOTE S\$LTM-SURVIVABILITY \$\$ VS LAND THREATS MULT (DIM)(FROM VULN AREAS)
A SR\$XX.K=FS\$AT*MIN(AA\$AT/(1-MS\$XX.K),SR\$MX.K*AV\$.K) (A-40\$)
NOTE SRS\$X-SORTIE RATE OF \$\$ VS XX (NUMBER PER DAY))
N FS\$AT=1-FS\$ST-FS\$LT (A-52\$)
NOTE FSS\$AT-FRACT U.S. AIRCRAFT SORTIES VS AIRCRAFT (DIM)
C AA\$AT=.02 (A-52.1\$)
NOTE AA\$AT-ALLOWABLE ATTR U.S. AIRCRAFT VS AIRBORNE THREATS (AC/DAY)
A \$AT.K=FS\$AT*\$.K (A-53\$)
NOTE \$AT-NUMBER OF \$\$ AIRCRAFT VS XX AIRCRAFT (AIRCRAFT)
A MS\$XX.K=EXP(-NARXX*(1-\$ARXX.K))*EXP(-NAIXX*(1-\$AIXX.K))
X *EXP(-NCXX*(1-\$CXX.K) (A-79\$)
NOTE MS\$XX-MISSION SURVIVABILILTY \$\$ AIRCRAFT VS XX AIRCRAFT (PROB)
C NARXX=1.5 (A-79.1\$)
NOTE NARXX-AVER. NO. OF RADAR GUIDED AAM ON XX AIRCRAFT
C NAIXX=1.5 (A-79.2\$)
NOTE NAIXX-AVER NO OF IR GUIDED AAM ON XX AIRCRAFT
C NCXX=1.0 (A-79.3\$)
NOTE NCXX-AVER. NO. OF CANNON ON XX AIRCRAFT
A \$ARXX.K=MS\$.K*S\$ARM (A-94\$)
NOTE \$ARXX-SURVIVABILITY OF \$\$ AIRCRAFT VS RADAR AAM ON XX (PROB)
C S\$ARM=1.005 (A-94.1\$)
NOTE S\$ARM-SURVIVABILITY OF \$\$ AIRCRAFT VS RADAR AAM MULT (DIM)
A \$AIXX.K=MS\$.K*S\$AIM (A-106\$)
NOTE \$AIXX-SURVIVABILITY OF \$\$ AIRCRAFT VS IR GUIDED AAM OF XX(PROB)
C S\$AIM=1.005 (A-106.1\$)
NOTE S\$AIM-SURVIVABILITY OF \$\$ AIRCRAFT VS IR GUIDED AAM MULT (DIM)
A \$CXX.K=MS\$.K*S\$CM (A-118\$)
NOTE \$CXX-SURVIVABILITY OF \$\$ AIRCRAFT VS CANNON FROM XX (PROB)
C S\$CM=1.007 (A-118.1\$)
NOTE S\$CM-SURVIVABILITY OF \$\$ AIRCRAFT VS CANNON MULT (DIM)
L XX.K=MAX(0,XX.J+(DT)(PMRXX.JK-ARXX.JK)) (A-1X)
N XX=XXN (A-1.1X)
NOTE XX-U.S.SR COMBAT AIRCRAFT (AIRCRAFT)
N XXN=15000 (A-1.2X)
NOTE XXN-U.S.SR COMBAT AIRCRAFT INITIALLY (AIRCRAFT)
R PMRXX.KL=CLIP(.03,25,TIME.K,WAR) (A-2X)
NOTE PMRXX-PROCUREMENT MINUS RETIREMENT RATE XX AIRCRAFT (AIRCRAFT/DAY)
R ARXX.KL=CLIP(XX.K*SRXXST.K*(1-MSXXST)+XX.K*SRXXLT.K*(1-MSXXLT)
X \$.K*SR\$XX.K*(1-MSXXSS.K),0,TIME.K,WAR) (A-3X)
NOTE ARXX-ATTRITION RATE OF XX AIRCRAFT (AIRCRAFT/DAY)
L CLXX.K=CLXX.J+(DT)(ARXX.JK) (A-4X)
N CLXX=0 (A-4.1X)
NOTE CLXX-CUMULATIVE LOSSES OF U.S.S.R COMBAT AIRCRAFT (AIRCRAFT)
A SRXXST.K=FSXXST*MIN(AAXXST/(1-MSXXST),SRXXM*AVXX.K) (A-6X)
NOTE SRXXST-SORTIE RATE U.S.S.R AIRCRAFT VS SEA THREATS (NUMBER PER DAY)

Fig. 3.2 (Cont.)

A AVXX.K=AV\$\$\$.K
NOTE AVXX - AVAILABILITY OF XX AIRCRAFT (PROB)
C SRXXM=4 (A-6.1X)
NOTE SRXXM-SORTIE RATE MAXIMUM FOR U.S.S.R COMBAT AIRCRAFT (NUMBER PER DAY)
C FSXXST=.2 (A-6.3X)
NOTE FSXXST-FRACT SORTIE XX VS SEA TARGET (DIM)
C AAXXST=.08 (A-6.4X)
NOTE AAXXST-ALLOWABLE ATTRITION XX VS SEA THREATS (AIRCRAFT/DAY)
C MSXXST=.95 (A-6.5X)
NOTE MSXXST-MISSION SURVIVABILITY XX AIRCRAFT VS SEA THREATS (PROB)
A SRXXLT.K=FSXXLT*MIN(AAXXLT/(1-MSXXLT),SRXXM*AVXX.K) (A-23X)
NOTE SRXXLT-SORTIE RATE XX AIRCRAFT VS LAND TARGETS (NUMBER PER DAY)
C FSXXLT=0.4 (A-23.1X)
NOTE FSXXLT-FRACTION SORTIE XX VS LAND TARGETS (DIM)
C AAXXLT=0.08 (A-23.2X)
NOTE AAXXLT-ALLOWABLE ATTRITION RATE XX VS LAND THREATS (AC/DAY)
C MSXXLT=0.95 (A-23.3X)
NOTE MSXXLT-MISSION SURVIVABILITY XX VS LAND THREATS (PROB)
A SRXX\$\$\$.K=FSXX\$\$*MIN(AA\$\$AT/(1-MS\$\$XX.K),SRXXM*AVXX.K) (A-40X)
NOTE SRXX\$\$-SORTIE RATE XX VS \$\$ AIRCRAFT (NUMBER PER DAY)
N FSXX\$\$=1-FSXXST-FSXXLT (A-52X)
NOTE FSXX\$\$-FRACT SORTIES XX AIRCRAFT VS \$\$ AIRCRAFT (DIM)
C AAXXAT=0.08 (A-52.1X)
NOTE AAXXAT-ALLOWABLE ATTRITION RATE XX VS AIRBORNE THREATS (AC/DAY)
A XXAT.K=FSXX\$\$*XX.K (A-53X)
NOTE XXAT-NUMBER OF XX AIRCRAFT VS \$\$ AIRCRAFT (AIRCRAFT)
A MSXX\$\$\$.K=0.95 (A-79X)
NOTE MSXX\$\$-MISSION SURVIVABILITY XX VS \$\$ (PROB)
NOTE *****
NOTE ***** MEASURES OF EFFECTIVENESS *****
NOTE *****
A TDB\$\$\$.K=CLIP(\$\$.K*SR\$\$LT.K*TDP\$\$\$,0,TIME.K,WAR) (A-214\$)
NOTE TDB\$\$-TARGETS DESTROYED BY \$\$ (TANK EQUIV TARGETS)
C TDP\$\$=2.25
NOTE TDP\$\$-TARGETS DESTROYED PER SORTIE \$\$ (TANK EQUIV TARGETS)
L CTDB\$\$\$.K=CTDB\$\$\$.J+(DT)(TDB\$\$\$.J) (A-215\$)
N CTDB\$\$=0 (A-215.1\$)
NOTE CTDB\$\$-CUM. TARGETS DESTROYED BY U.S. AIRCRAFT (TANK EQUIV TARGETS)
A TDP\$\$L.K=CTDB\$\$\$.K/CL\$\$\$.K (A-217\$)
NOTE TDP\$\$-TARGETS DESTROYED PER \$\$ LOST (TARGETS/AIRCRAFT)
A KPs\$\$L.K=CLXX.K/CL\$\$\$.K (A-218\$)
NOTE KPs\$\$L-KILLS PER \$\$ LOST (AIRCRAFT/AIRCRAFT)
A TDBXX.K=CLIP(XX.K*SRXXLT.K*TDP\$XX,0,TIME.K,WAR) (A-214X)
NOTE TDBXX-TARGETS DESTROYED BY XX(TANK EQUIV TARGETS)
C TDP\$XX=1.33 (A-214.1X)
NOTE TDP\$XX-TARGETS DESTROYED PER SORTIE XX (TANK EQUIV TARGETS)
L CTDBXX.K=CTDBXX.J+(DT)(TDBXX.J) (A-215X)
N CTDBXX=0 (A-215.1X)
NOTE CTDBXX-CUMULATIVE TARGETS DESTROYED BY XX (TANK EQUIV TARGETS)
A TDPXXL.K=CTDBXX.K/CLXX.K (A-217X)
NOTE TDPXXL-TARGETS DESTROYED PER XX LOST (TANK EQUIV TARGETS)

Fig. 3.2 (Cont.)

A KPXXL.K=CL\$\$K/CLXX.K (A-218X)
NOTE KPXXL-KILLS PER XX LOST (AC/AC)
L COMVRR.K=COMVRR.J+(DT/TRRCE)(COMVR.J-COMVRR.J) (A-219)
N COMVRR=1.0
NOTE COMVRR-U.S./ U.S.S.R AIR COMBAT VALUE RATIO RECOGNIZED (DIM)
C TRRCE=3 (A-219.1)
NOTE TRRCE-TIME TO RECOGNIZE RELATIVE AIR COMBAT EFFECTIVENESS (YR)
A COMVR.K=CVRN.K/CVRD.K (A-220)
NOTE COMVR-U.S./ U.S.S.R AIR COMBAT VALUE (DIM)
A CVRN.K=((\$\$.K*F\$XX\$AT-((PMRRXX.JK*F\$XX\$S\$)/(TCF.K*F\$XX\$.K)))
X *SQRT(F\$XX\$.K) (A-221-\$)
NOTE CVRN-COMBAT VALUE RATIO NUMERATOR
A CVRD.K=(XX.K*F\$XX\$S\$-((PR\$\$.JK*F\$XX\$AT)/(TCF.K*F\$XX\$.K)))
X *SQRT(F\$XX\$.K) (A-221-X)
NOTE CVRD-COMBAT VALUE RATIO DENOMINATOR
A TCF.K=CLIP(360,1,WAR,TIME.K) (A-221.1)
NOTE TCF-TIME CHANGE FACTOR (DAYS-YRS)
A F\$XX\$.K=SR\$XX\$.K*(1-MS\$XX\$.K) (A-223-\$)
NOTE F\$XX\$-EFFECTIVENESS OF \$\$ VS XX AIRCRAFT (DIM)
A FXX\$\$.K=SRXX\$\$.K*(1-MS\$XX\$.K) (A-223-X)
NOTE FXX\$\$-EFFECTIVENESS OF XX VS \$\$ AIRCRAFT (DIM)
NOTE *****
NOTE ***** AVAILABILITY COMPONENT *****
NOTE *****
A \$\$MTBM.K=\$\$TBMN*\$\$TBMBM.K (AV-6)
NOTE \$\$MTBM-\$\$ MEAN TIME BETWEEN MAINTENANCE (DAYS)
A \$\$TBMBM.K=TABLE(T\$TBMBM,\$\$RDBR.K,0,2,0.2) (AV-6.1)
NOTE T\$TBMBM=7/4/2.5/1.8/1.3/1/0.8/0.65/0.55/0.5/0.47 (AV-6.2)
T T\$TBMBM=.47/.5/.55/.65/.8/1/1.3/1.8/2.5/4/7 (AV-6.2)
NOTE \$\$TBMBM-\$\$ TIME BETWEEN MAINTENANCE BUDGET MULT.(DAYS)
C \$\$TBMN=4 (AV-6.3)
NOTE \$\$TBMN-\$\$ TIME BETWEEN MAINTENANCE NORMAL (DAYS)
A \$\$MTBF.K=\$\$TBFN*\$\$TBFBM.K (AV-13)
NOTE \$\$MTBF-\$\$ MEAN TIME BETWEEN FAILURE (DAYS)
A \$TBFBM.K=TABLE(T\$TBFBM.K,\$\$RDBR.K,0,2,0.2) (AV-13.1)
NOTE T\$TBFBM=7/4/2.5/1.8/1.3/0.8/0.65/0.55/0.5/0.47/.47 (AV-13.2)
T T\$TBFBM=.47/.47/.5/.55/.65/.8/1.3/1.8/2.5/4/7 (AV-13.2)
NOTE \$TBFBM-\$\$ TIME BETWEEN FAILURE BUDGET MULT. (DIM)
C \$\$TBFN=3 (AV-13.3)
NOTE \$\$TBFN-\$\$ TIME BETWEEN FAILURE NORMAL (DAYS)
A \$\$MMDT.K=\$\$MMDTN*\$\$MMDTBM.K (AV-14)
NOTE \$\$MMDT-\$\$ MEAN MAINTENANCE DOWN TIME (DAYS)
C \$\$MMDTN=1.0 (AV-15)
NOTE \$\$MMDTN-\$\$ MEAN MAINTENANCE DOWN TIME NORMAL (DAYS)
A \$\$MMDTBM.K=TABHL(T\$\$MMDBM,\$\$SOMBR.K,0,2,0.2) (AV-16)
T T\$\$MMDBM=10/5/3/2/1.4/1/0.75/0.6/0.5/0.44/.40 (AV-16.1)
NOTE \$\$MMDTBM-\$\$MEAN MAINT. DOWN TIME O&M BUDGET MULT. (DAYS)
A \$\$MTTR.K=\$\$TTRN*\$\$TTRBM.K (AV-17)
NOTE \$\$MTTR-\$\$ MEAN TIME TO REPAIR (DAYS)
C \$\$TTRN=2 (AV-18)
NOTE \$\$TTRN-\$\$ MEAN TIME TO REPAIR NORMAL (DAYS)

Fig. 3.2 (Cont.)

A $\$TTRBM.K = TABLE(T\$ATRBM, \$\$OMBR.K, 0, 2, 0.2)$ (AV-19)
T $T\$ATRBM = 10/5/3/2/1.4/1/0.75/0.6/0.5/0.44/0.4$ (AV-19.1)
NOTE $\$TTRBM-\$ \$$ MEAN TIME TO REPAIR O&M BUDGET MULT. (DIM)
A $\$ \$OMBR.K = FDOM.K / FDOMN$ (AV-20)
NOTE $\$ \$OMBR-\$ \$$ O&M BUDGET RATIO (DIM)
C $FDOMN = 0.4$ (AV-20.1)
NOTE $FDOMN$ -FRACT DOD BUDGET TO O&M NORMAL (DIM)
A $\$ \$RDBR.K = FDRD.K / FDRDN$ (AV-21)
NOTE $\$ \$RDBR-\$ \$$ R&D BUDGET RATIO (DIM)
C $FDRDN = .10$ (AV-21.1)
NOTE $FDRDN$ -FRACT DOD BUDGET TO R&D NORMAL (DIM)
A $AV\$ \$.K = 1 / (1 + (\$ \$MMDT.K / \$ \$MTBM.K) + (\$ \$MTTR.K / \$ \$MTBF.K))$ (AV-23)
NOTE $AV\$ \$$ -AVAILABILITY OF $\$ \$$ AIRCRAFT
NOTE *****
NOTE ***** SURVIVABILITY SUBMODEL *****
NOTE *****
L $MS\$ \$.K = MS\$ \$.J + CLIP(0, (DT/SCT.J)(FMS\$ \$.J - MS\$ \$.J), TIME.J, WAR)$ (SS-1)
N $MS\$ \$N = MS\$ \N (SS-1.1)
NOTE $MS\$ \$$ -SURVIVABILITY OF U.S. COMBAT AIRCRAFT (PROB)
C $MS\$ \$N = 0.975$ (SS-1.2)
NOTE $MS\$ \N -SURVIV OF U.S. COMBAT AIRCRAFT NORMAL (PROB)
A $SCT.K = TABLE(SCTT, \$ \$RDBR.K, 0, 2, 0.5)$ (SS-1.3)
T $SCTT = 80/40/20/10/5$ (SS-1.4)
NOTE SCT -SURVIVABILITY CHANGE TIME (YEARS)
A $FMS\$ \$.K = MS\$ \$N + MS\$ \$AE.K + MS\$ \$TE.K$ (SS-2)
NOTE $FMS\$ \$$ -FORECASTED MISSION SURVIVABILITY OF $\$ \$$ (PROB)
A $MS\$ \$AE.K = CLIP(((SM.K - SB.K) / (1 - SB.K)) (1 - MS\$ \$N) / 2, 0, IPDTPL.K, 0)$ (SS-3)
NOTE $MS\$ \AE -SURVIV OF $\$ \$$ DUE TO AIRCRAFT ENHANCEMENT (PROB)
A $MS\$ \$TE.K = ((SBF.K - SB.K) / (1 - SB.K)) (1 - MS\$ \$N) / 2$ (SS-4)
NOTE $MS\$ \TE -SURVIV OF $\$ \$$ DUE TO THREAT ENHANCEMENT (PROB)
A $SB.K = SBSUBSY$ (SS-4.1)
NOTE SB -SURVIV OF GENERIC BASELINE AIRCRAFT IN BASE YEAR (PROB)
C $SBSUBSY = 0.96$ (SS-4.2)
NOTE $SBSUBSY$ -VALUE OF SB FROM SUBSYSTEM MODEL OUTPUT (PROB)
A $SBF.K = 1 - SUSCE.K * VULNE.K$ (SS-5.1)
NOTE SBF -SURVIV OF GENERIC BASELINE AIRCRAFT IN FORECAST YEAR (PROB)
A $SM.K = SB.K * (1 - DS.K)$ (SS-5.2)
NOTE SM -SURVIV OF GENERIC MODIFIED AIRCRAFT IN BASE YEAR (PROB)
A $DS.K = DSN$ (SS-6)
C $DSN = -.0175$
NOTE DS -DELTA SURVIVABILITY (DIM)
A $DW.K = -.081$ (SS-47)
NOTE DW -DELTA WEIGHT AIRCRAFT $\$ \$$ (DIM)
A $DA.K = DAN$ (SS-88)
C $DAN = -.33$
NOTE DA -DELTA AQUISITION COST AIRCRAFT $\$ \$$ (DIM)
A $DM.K = -.002$ (SS-129)
NOTE DM -DELTA MAINTENANCE COST AIRCRAFT $\$ \$$ (DIM)
A $SUSCE.K = .4$
NOTE $SUSCE$ -SUSCEPTIBILITY OF AIRCRAFT TO ENHANCED THREAT (PROB)
A $VULNE.K = .4$ (SS-259)

Fig. 3.2 (Cont.)

NOTE VULNE-ENHANCED WEIGHTED PROB KILL/HIT ON \$\$ (PROB)

A $DPL.K = (PB - PM.K) / PB$ (SS-170)

NOTE DPL - DELTA PAYLOAD (PROB)

C $PB = 18000$ (SS-170.1)

NOTE PB - PAYLOAD OF BASELINE AIRCRAFT (LBS)

A $PM.K = ((WB + PB + FBB - WM.K) / FBB) (2 * WB + PB) - 2 * WM.K / (1 + ((2 * WB + PB) / FBB))$

NOTE PM - PAYLOAD OF MODIFIED AIRCRAFT (LBS)

C $WB = 26000$ (SS-171.1)

NOTE WB - WEIGHT (EMPTY) OF BASELINE AIRCRAFT (LBS)

C $FBB = 16000$ (SS-171.2)

NOTE FBB - FUEL WEIGHT OF BASELINE AIRCRAFT (LBS)

A $WM.K = WB * (1 - DW.K * ROTOR - DW.K * FIXED - DW.K * VTOL)$ (SS-172)

NOTE WM - WEIGHT (EMPTY) OF MODIFIED AIRCRAFT (LBS)

C $ROTOR = 0$ (SS-172.1)

C $FIXED = 1$ (SS-172.2)

C $VTOL = 0$ (SS-172.3)

NOTE CONSTANTS FOR IDENTIFYING TYPE OF AIRCRAFT U.S.ED

A $MSB.K = SB.K * ROTOR + SB.K * FIXED + SB.K * VTOL$ (SS-173)

NOTE MSB - MISSION SURVIVABILITY OF BASELINE AIRCRAFT (PROB)

A $MSM.K = SM.K * ROTOR + SM.K * FIXED + SM.K * VTOL$ (SS-174)

NOTE MSM - MISSION SURVIVABILITY OF MODIFIED AIRCRAFT (PROB)

A $SR\$M.K = (PM.K / PB) * SR\B (SS-175)

NOTE SR\\$M - SORTIE RATE OF MODIFIED AIRCRAFT (NUMBER PER DAY)

C $SR\$B = 2$ (SS-175.1)

NOTE SR\\$B - SORTIE RATE OF BASELINE AIRCRAFT (NUMBER PER DAY)

A $A\$M.K = A\$B / (1 - DM.K)$ (SS-176)

NOTE A\\$M - AVAILABILITY OF MODIFIED AIRCRAFT (PROB)

C $A\$B = .5$

NOTE A\\$B - AVAILABILITY OF BASELINE AIRCRAFT

A $\$MNN.K = \$\$BN / (1 - DA.K)$ (SS-177)

NOTE \\$MNN - NUMBER OF MODIFIED AIRCRAFT INITIALLY (AIRCRAFT)

C $\$\$BN = 720$ (SS-177.1)

NOTE \\$\\$BN - NUMBER OF BASELINE AIRCRAFT INITIALLY (AIRCRAFT)

NOTE *****

NOTE ***** ANALYTICAL SOLUTION OF ATTRITION MODEL *****

NOTE *****

NOTE

A $\$SB.K = (((\$MNN.K / B.K) * (R1.K + LAM1.K) (R1.K + LAM2.K)) * (E1.K - E2.K) + \$\$BN * ((R1.K + LAM1.K) * E1.K - (R1.K + LAM2.K) * E2.K)) / (LAM1.K - LAM2.K)$

X

NOTE SSB - NUMBER OF BASELINE AIRCRAFT AT THE END OF THE WAR (AIRCRAFT)

A $\$MD.K = (B.K * \$\$BN * (E2.K - E1.K) + \$MNN.K * ((R1.K + LAM1.K) * E2.K - (R1.K + LAM2.K) * E1.K)) / (LAM1.K - LAM2.K)$

X

NOTE $\$MD$ - NUMBER OF MODIFIED AIRCRAFT AT THE END OF THE WAR (AIRCRAFT)

A $B.K = SR\$B * A\$B * (1 - MSM.K)$

NOTE B - ATTRITION FACTOR OF MODIFIED AIRCRAFT DUE TO AIR THREAT

A $R1.K = SR\$M.K * A\$M.K * (1 - MSM.K)$

NOTE R1 - ATTRITION FACTOR OF MODIFIED AIRCRAFT DUE TO SURFACE THREAT

A $C.K = SR\$M.K * A\$M.K * (1 - MSB.K)$

NOTE C - ATTRITION FACTOR OF BASELINE AIRCRAFT DUE TO AIR THREAT

A $R2.K = SR\$B * A\$B * (1 - MSB.K)$

NOTE R2 == ATTRITION FACTOR OF BASELINE AIRCRAFT DUE TO SURFACE THREAT

Fig. 3.2 (Cont.)

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A   LAM1.K=(-(R1.K+R2.K)+SQRT((R1.K-R2.K)*(R1.K-R2.K)+4*B.K*C.K))/2
A   LAM2.K=(-(R1.K+R2.K)-SQRT((R1.K-R2.K)*(R1.K-R2.K)+4*B.K*C.K))/2
A   E1.K=EXP(LAM1.K*T.K)
A   E2.K=EXP(LAM2.K*T.K)
A   T.K=CLIP((1/(LAM1.K-LAM2.K))*LOGN(Q1.K+((\$MNN.K/B.K)*(R1.K+LAM1.K)
X     *(R1.K+LAM2.K)+\$\$BN*(R1.K+LAM2.K))/((\$MNN.K/B.K)*(R1.K+LAM1.K)
X     *(R1.K+LAM2.K)+\$\$BN*(R1.K+LAM1.K))), (1/(LAM1.K-LAM2.K))*LOGN(Q2.K
X     +(B.K*\$\$BN+\$MNN.K*(R1.K+LAM1.K))/(B.K*\$\$BN+\$MNN.K*(R1.K+LAM2.K)))
X     ,\$\$BL1D.K,\$\$ML1D.K)
NOTE T - THE TIME AT WHICH THE WAR END (DAYS)
A   \$\$BL1D.K=(C.K*\$MNN.K+R2.K*\$\$BN)/\$\$BN
NOTE \$\$BL1D - FRACTION LOST OF BASELINE AC ON THE FIRST STRIKE (FRACT)
A   \$\$ML1D.K=(B.K*\$\$BN+R1.K*\$MNN.K)/\$MNN.K
NOTE \$\$ML1D - FRACTION LOST OF MODIFIED AC ON THE FIRST STRIKE (FRACT)
A   Q1.K=CLIP(0,100,\$\$BL1D.K,\$\$ML1D.K)
A   Q2.K=CLIP(100,0,\$\$BL1D.K,\$\$ML1D.K)
NOTE Q1 AND Q2 ARE CONSTANTS TO ELIMINATE THE LOG OF NEGATIVE NUMBERS
A   I\$\$B.K=(((\$MNN.K/B.K)*(R1.K+LAM1.K)(R1.K+LAM2.K))*((1/LAM1.K)
X     *(E1.K-1)-(1/LAM2.K)*(E2.K-1))+\$\$BN*((R1.K+LAM1.K)/LAM1.K)
X     *(E1.K-1)-((R1.K+LAM2.K)/LAM2.K)*(E2.K-1)))/(LAM1.K-LAM2.K)
NOTE I\$\$B - INTEGRATION OF \$\$B FROM T=0 TO T=T
A   I\$\$M.K=(B.K*\$\$BN*((E2.K-1)/LAM2.K)-(E1.K-1)/LAM1.K)+\$MNN.K*((R1.K
X     +LAM1.K)*((E2.K-1)/LAM2.K)-(R1.K+LAM2.K)*((E1.K-1)/LAM1.K))
X     /(LAM1.K-LAM2.K)
NOTE I\$\$M - INTEGRATION OF \$\$M FROM T=0 TO T=T
A   \$\$BL.K=SR\$\$B*A\$\$B*(1-MSB.K)*I\$\$B.K+SR\$\$M.K*A\$\$M.K*(1-MSB.K)*I\$\$M.K
NOTE \$\$BL - NUMBER OF BASELINE AIRCRAFT LOST (AIRCRAFT)
A   \$\$ML.K=SR\$\$M.K*A\$\$M.K*(1-MSM.K)*I\$\$M.K+SR\$\$B*A\$\$B*(1-MSM.K)*I\$\$B.K
NOTE \$\$ML - NUMBER OF MODIFIED AIRCRAFT LOST (AIRCRAFT)
A   DPLCC.K=1-((1-\$SMD.K/\$MNN.K)/(1-\$\$B.K/\$\$BN))
NOTE DPLCC - DECREASED PROGRAM LIFE CYCLE COST (FRACT)
A   PDTPBL.K=2*SR\$\$B*A\$\$B*I\$\$B.K*PB/\$\$BL.K
NOTE PDTPBL - CUMULATIVE PAYLOAD DELIVER PER BASELINE AC LOST (LBS)
A   PDTPML.K=2*SR\$\$M.K*A\$\$M.K*I\$\$M.K*PM.K/\$\$ML.K
NOTE PDTPML - CUMULATIVE PAYLOAD DELIVER PER MODIFIED AC LOST (LBS)
A   IPDTPL.K=(PDTPML.K-PDTPBL.K)/PDTPBL.K
NOTE IPDTPL - INCREASED PAYLOAD DELIVERED TO TARGET PER AC LOST
SPEC DT=1/PRTPER=5/PLTPER=1/LENGTH=2030
PRINT \$\$U,\$\$M,\$\$ ,XX
PRINT GNP,AR\$$,ARXX,AV\$$,MS\$$
PRINT COMVR,IPDTPL,DPLCC,PDTPBL,PDTPML
PRINT KP\$\$L,KPXXL,TDP\$\$L,TDPXXL,COMVRR
PRINT CL\$$,CLXX,CTDB\$$,CTDBXX,CVRN,CVRD
PRINT FX\$$,F\$\$XX,MS\$\$XX,SR\$\$XX,SRXX\$$
NOTE PRINT T,LAM1,LAM2,B,R1,C,R2,\$\$BL1D,\$\$ML1D,I\$\$B,I\$\$M,\$\$BL,\$\$ML
PLOT \$\$U=\$\$U,\$\$M=\$\$M,\$\$=\$ ,XX=X
RUN
QUIT

```

Fig. 3.2 (Cont.)

3.8 RESULTS OF THE SIMULATION USING PC SURMAN

The results of the computer simulation using PC SURMAN are discussed in this section. The printout of results obtained using the model are shown in Figure 3.3.

The main points of interest are the measures of efficiency that are the outputs. These are indicators of the performance of the two forces. It is observed that the increase in payload delivered to target (ITDPL) has a value of 1.783 which is great than 0. What this means is that the payload delivered to target per aircraft lost is greater for modified aircraft when compared to the baseline aircraft. In other words the modified attack aircraft is better than the baseline attack aircraft based on the criterion of payload delivered per loss.

The decreased program life cycle cost (DPLCC) has a value of 0.6129 which is also greater than 0. This again indicates that the modified fighter aircraft is better than the baseline fighter aircraft with respect to life cycle cost.

The combat value ratio (COMVR) has a value of 1.02 in 1980. This indicates that the U.S. force (\$\$) is superior to the U.S.S.R. force (XX). It is however, interesting to note that COMVR changes with time and is steadily increasing. The reason for this is that in calculating COMVR the current inventories of the two forces are used. The attrition rate of the U.S.S.R. aircraft (ARXX) is much higher than that of the U.S. force (AR\$\$). This means that the XX inventory depletes at a faster rate than the \$\$ inventory. Also the mission survivability of \$\$ (MSS\$) is enhanced due to modification of aircraft. This causes the mission survivability

of \$\$ versus XX (MS\$\$XX) to increase, which in turn leads to an increase in the effectiveness of \$\$ versus XX aircraft (F\$\$XX). These result in the increasing trend of COMVR.

It is also to be noted that the effectiveness of \$\$ versus XX (F\$\$XX) is greater than that of XX versus \$\$ (FXX\$\$) which would lead one to believe that \$\$ is superior. It is, however, to be borne in mind that the relative sizes of the inventories also plays a crucial role in deciding the winner. COMVR is a measure of effectiveness that takes this into account. Another point of interest is that the mission survivability of \$\$ due to threat enhancement (MS\$\$TE) is negative which implies that the threat has become more effective. However, the mission survivability due to aircraft enhancement (MS\$\$AE) more than compensates for that, thus resulting in a net increase in mission survivability (MS\$\$).

Once the war starts it is observed that the targets destroyed per aircraft lost for XX (TDPXXL) is less than that for \$\$ (TDP\$\$L). This may induce one to believe that \$\$ will win. But, the rate at which \$\$ and XX aircraft are lost also matter. The attrition rate of \$\$ is less than that of XX. The kills per \$\$ aircraft lost (KP\$\$L) is greater than 1 indicating that \$\$ enjoys air superiority over XX.

TIME= 1980. \$\$U=13.00T \$\$M= .00 \$\$=13.00T XX=15.00T
 GNP= 2.77R AR\$\$= .0 ARXX= 150.0 AV\$\$= .4800 MS\$\$= .9750
 COMVR= 1.02 IPDTPL= 1.783 DPLCC= .6129 PDTPBL=427.8T PDTPML=1190.T
 KP\$\$L= .000 TDP\$\$L= .00 TDPXXL= .000 COMVRR= 1.000 CL\$\$= 0.
 CLXX= .00 CTDB\$\$= .0 CTDBXX= .0 CVRN= 543.2 CVRD= 535.
 FXN\$\$=8.000A F\$\$XX=10.92A MS\$\$XX= .9414 SR\$\$XX= .1365 SRXX\$\$= .1365
 MS\$\$AE=7.800A MS\$\$TE=-3.125A SBF= .9500 SM= .9850

 TIME= 1985. \$\$U= .14T \$\$M=12.87T \$\$=13.01T XX=14.39T
 GNP= 3.86R AR\$\$= 128.7 ARXX= 143.9 AV\$\$= .4486 MS\$\$= .9761
 COMVR= 1.09 IPDTPL= 1.783 DPLCC= .6129 PDTPBL=427.8T PDTPML=1190.T
 KP\$\$L= .000 TDP\$\$L= .00 TDPXXL= .000 COMVRR= 1.047 CL\$\$= 299.
 CLXX= .74T CTDB\$\$= .0 CTDBXX= .0 CVRN= 558.0 CVRD= 513.
 FXN\$\$=8.000A F\$\$XX=11.51A MS\$\$XX= .9444 SR\$\$XX= .1439 SRXX\$\$= .1439
 MS\$\$AE=7.800A MS\$\$TE=-3.125A SBF= .9500 SM= .9850

 TIME= 1990. \$\$U= .17T \$\$M=12.98T \$\$=13.14T XX=13.80T
 GNP= 5.62R AR\$\$= 129.8 ARXX= 138.0 AV\$\$= .4706 MS\$\$= .9769
 COMVR= 1.17 IPDTPL= 1.783 DPLCC= .6129 PDTPBL=427.8T PDTPML=1190.T
 KP\$\$L= .000 TDP\$\$L= .00 TDPXXL= .000 COMVRR= 1.121 CL\$\$= 944.
 CLXX= 1.45T CTDB\$\$= .0 CTDBXX= .0 CVRN= 576.1 CVRD= 492.
 FXN\$\$=8.000A F\$\$XX=12.02A MS\$\$XX= .9467 SR\$\$XX= .1502 SRXX\$\$= .1502
 MS\$\$AE=7.800A MS\$\$TE=-3.125A SBF= .9500 SM= .9850

Fig 3.3 Simulation Results of PC SURMAN

TIME= 1995. \$\$U= .00 \$\$M=13.40T \$\$=13.40T XX=13.25T

 GNP= 8.13R AR\$\$= 134.0 ARXX= 132.5 AV\$\$= .4800 MS\$\$= .9775

COMVR= 1.26 IPDTPL= 1.783 DPLCC= .6129 PDTPBL=427.8T PDTPML=1190.T

KP\$\$L= .000 TDP\$\$L= .00 TDPXXL= .000 COMVRR= 1.206 CL\$\$= 1604.

 CLXX= 2.12T CTDB\$\$= .0 CTDBXX= .0 CVRN= 597.5 CVRD= 474.

FXX\$\$=8.000A F\$\$XX=12.44A MS\$\$XX= .9486 SR\$\$XX= .1555 SRXX\$\$= .1555

MS\$\$AE=7.800A MS\$\$TE=-3.125A SBF= .9500 SM= .9850

TIME= 2000. \$\$U= .00 \$\$M=13.83T \$\$=13.83T XX=12.72T

 GNP=11.55R AR\$\$= 138.3 ARXX= 787.6 AV\$\$= .4800 MS\$\$= .9780

COMVR= 1.37 IPDTPL= 1.783 DPLCC= .6129 PDTPBL=427.8T PDTPML=1190.T

KP\$\$L= 1.217 TDP\$\$L= .00 TDPXXL= .000 COMVRR= 1.306 CL\$\$= 2282.

 CLXX= 2.78T CTDB\$\$= .0 CTDBXX= .0 CVRN= 625.5 CVRD= 455.

FXX\$\$=8.000A F\$\$XX=12.79A MS\$\$XX= .9500 SR\$\$XX= .1599 SRXX\$\$= .1599

MS\$\$AE=7.800A MS\$\$TE=-3.125A SBF= .9500 SM= .9850

TIME= 2005. \$\$U= .00 \$\$M=12.68T \$\$=12.68T XX= 9.17T

 GNP=11.55R AR\$\$= 233.5 ARXX= 602.4 AV\$\$= .4800 MS\$\$= .9780

COMVR= 1.75 IPDTPL= 1.783 DPLCC= .6129 PDTPBL=427.8T PDTPML=1190.T

KP\$\$L= 1.839 TDP\$\$L= 11.04 TDPXXL= 7.551 COMVRR= 1.391 CL\$\$= 3440.

 CLXX= 6.33T CTDB\$\$= 38.0T CTDBXX= 47.8T CVRN= 573.5 CVRD= 328.

FXX\$\$=8.000A F\$\$XX=12.79A MS\$\$XX= .9500 SR\$\$XX= .1599 SRXX\$\$= .1599

MS\$\$AE=7.800A MS\$\$TE=-3.125A SBF= .9500 SM= .9850

TIME= 2010. \$\$U= .00 \$\$M=11.59T \$\$=11.59T XX= 6.46T

GNP=11.55R AR\$\$= 197.1 ARXX= 458.5 AV\$\$= .4800 MS\$\$= .9780
 COMVR= 2.27 IPDTPL= 1.783 DPLCC= .6129 PDTPBL=427.8T PDTPML=1190.T
 KP\$\$L= 1.994 TDP\$\$L= 16.02 TDPXXL= 9.069 COMVRR= 1.934 CL\$\$= 4532.
 CLXX= 9.04T CTDB\$\$= 72.6T CTDBXX= 82.0T CVRN= 524.4 CVRD= 231.
 FXX\$\$=8.000A F\$\$XX=12.79A MS\$\$XX= .9500 SR\$\$XX= .1599 SRXX\$\$= .1599
 MS\$\$AE=7.800A MS\$\$TE=-3.125A SBF= .9500 SM= .9850

 TIME= 2015. \$\$U= .00 \$\$M=10.67T \$\$=10.67T XX= 4.40T

GNP=11.55R AR\$\$= 168.3 ARXX= 347.9 AV\$\$= .4800 MS\$\$= .9780
 COMVR= 3.06 IPDTPL= 1.783 DPLCC= .6129 PDTPBL=427.8T PDTPML=1190.T
 KP\$\$L= 2.033 TDP\$\$L= 19.12 TDPXXL= 9.531 COMVRR= 2.576 CL\$\$= 5457.
 CLXX=11.10T CTDB\$\$=104.4T CTDBXX=105.8T CVRN= 482.8 CVRD= 158.
 FXX\$\$=8.000A F\$\$XX=12.79A MS\$\$XX= .9500 SR\$\$XX= .1599 SRXX\$\$= .1599
 MS\$\$AE=7.800A MS\$\$TE=-3.125A SBF= .9500 SM= .9850

 TIME= 2020. \$\$U= .00 \$\$M= 9.89T \$\$= 9.89T XX= 2.84T

GNP=11.55R AR\$\$= 145.4 ARXX= 262.9 AV\$\$= .4800 MS\$\$= .9780
 COMVR= 4.40 IPDTPL= 1.783 DPLCC= .6129 PDTPBL=427.8T PDTPML=1190.T
 KP\$\$L= 2.025 TDP\$\$L= 21.38 TDPXXL= 9.615 COMVRR= 3.577 CL\$\$= 6251.
 CLXX=12.66T CTDB\$\$=133.7T CTDBXX=121.7T CVRN= 447.1 CVRD= 102.
 FXX\$\$=8.000A F\$\$XX=12.79A MS\$\$XX= .9500 SR\$\$XX= .1599 SRXX\$\$= .1599
 MS\$\$AE=7.800A MS\$\$TE=-3.125A SBF= .9500 SM= .9850

 TIME= 2025. \$\$U= .00 \$\$M= 9.20T \$\$= 9.20T XX= 1.67T

GNP=11.55R AR\$\$= 127.0 ARXX= 197.7 AV\$\$= .4800 MS\$\$= .9780
 COMVR= 6.98 IPDTPL= 1.783 DPLCC= .6129 PDTPBL=427.8T PDTPML=1190.T

KP\$\$L= 1.994 TDP\$\$L= 23.18 TDPXXL= 9.518 COMVRR= 5.368 CL\$\$= 6939.
CLXX=13.83T CTDB\$\$=160.9T CTDBXX=131.7T CVRN= 416.2 CVRD= 60.
FXX\$\$=8.000A F\$\$XX=12.79A MS\$\$XX= .9500 SR\$\$XX= .1599 SRXX\$\$= .1599
MS\$\$AE=7.800A MS\$\$TE=-3.125A SBF= .9500 SM= .9850

- - - - -

TIME= 2030. \$\$U= .00 \$\$M= 8.61T \$\$= 8.61T XX= .78T
GNP=11.55R AR\$\$= 112.2 ARXX= 147.7 AV\$\$= .4800 MS\$\$= .9780
COMVR= 13.89 IPDTPL= 1.783 DPLCC= .6129 PDTPBL=427.8T PDTPML=1190.T
KP\$\$L= 1.951 TDP\$\$L= 24.69 TDPXXL= 9.321 COMVRR= 9.401 CL\$\$= 7543.
CLXX=14.72T CTDB\$\$=186.2T CTDBXX=137.2T CVRN= 389.2 CVRD= 28.
FXX\$\$=8.000A F\$\$XX=12.79A MS\$\$XX= .9500 SR\$\$XX= .1599 SRXX\$\$= .1599
MS\$\$AE=7.800A MS\$\$TE=-3.125A SBF= .9500 SM= .9850

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4.0 SURVIVABILITY TRADEOFF ANALYSIS

4.1 INTRODUCTION - APPLICATION OF SURMAN TO CONCEPTUAL DESIGN

When an additional modification is made to an existing baseline aircraft to enhance survivability, some penalties may be incurred due to additional costs, maintainability, reliability, logistics, or other pertinent operational factors associated with the modification. If the modification is large in terms of installation size and weight, it may also have a significant impact on the performance of existing operational aircraft. In the case of new aircraft designs, additional costs can result due to an increase in aircraft overall size and gross weight necessary to accommodate the modification assuming the basic mission performance requirements remain constant. It is in the initial design phases, where there is opportunity to obtain the survivability benefits at the least and, in some cases, no penalty. A classic example is the arrangement of the airframe and subsystems to provide natural shielding of the crew or essential subsystems. Air vehicle configuration analysis methods are used by the aircraft designer to evaluate the significance of design changes and modifications on aircraft characteristics and performance for new aircraft designs and existing designs, as required throughout the aircraft's life cycle. Aircraft performance characteristics calculations include mission radius, range, speed and

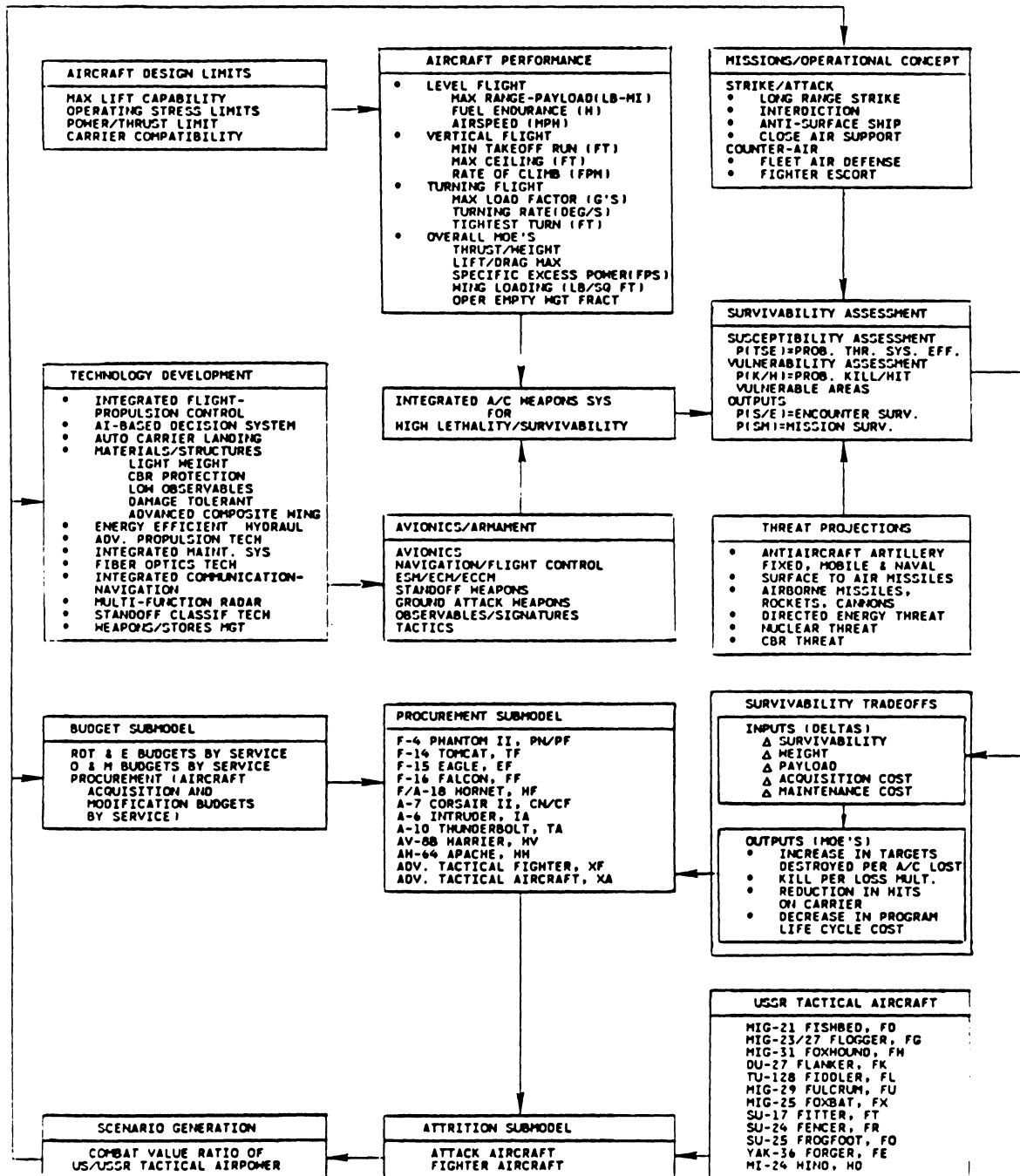
time, take-off and landing distances, maneuver load factor, specific excess power, etc. Variable design parameters include external shapes and areas (wing loading), thrust/weight ratios, gross weight, fuel weight, weight and volume of avionics and armament subsystems, operating items and/or payload, etc. The sensitivity of design changes on aircraft performance can vary considerably depending on the type of aircraft involved, mission requirements, and the nature of the change. Figure 4.1 is a block diagram representation of the iterative conceptual design procedure.

Referring to Figure 4.1, key elements in the process are survivability assessment and survivability tradeoff analysis. The survivability assessment process has been treated in Chapter 2. This Chapter describes the survivability tradeoff analysis.

Figures 4.2 and 4.3 [6] present the methodology invoked in the tradeoff studies approach. Referring to Figure 4.1, it is seen that the inputs for the tradeoff analysis are obtained from the survivability assessment. The key tradeoff factors can be divided into two categories -- the inputs and the outputs.

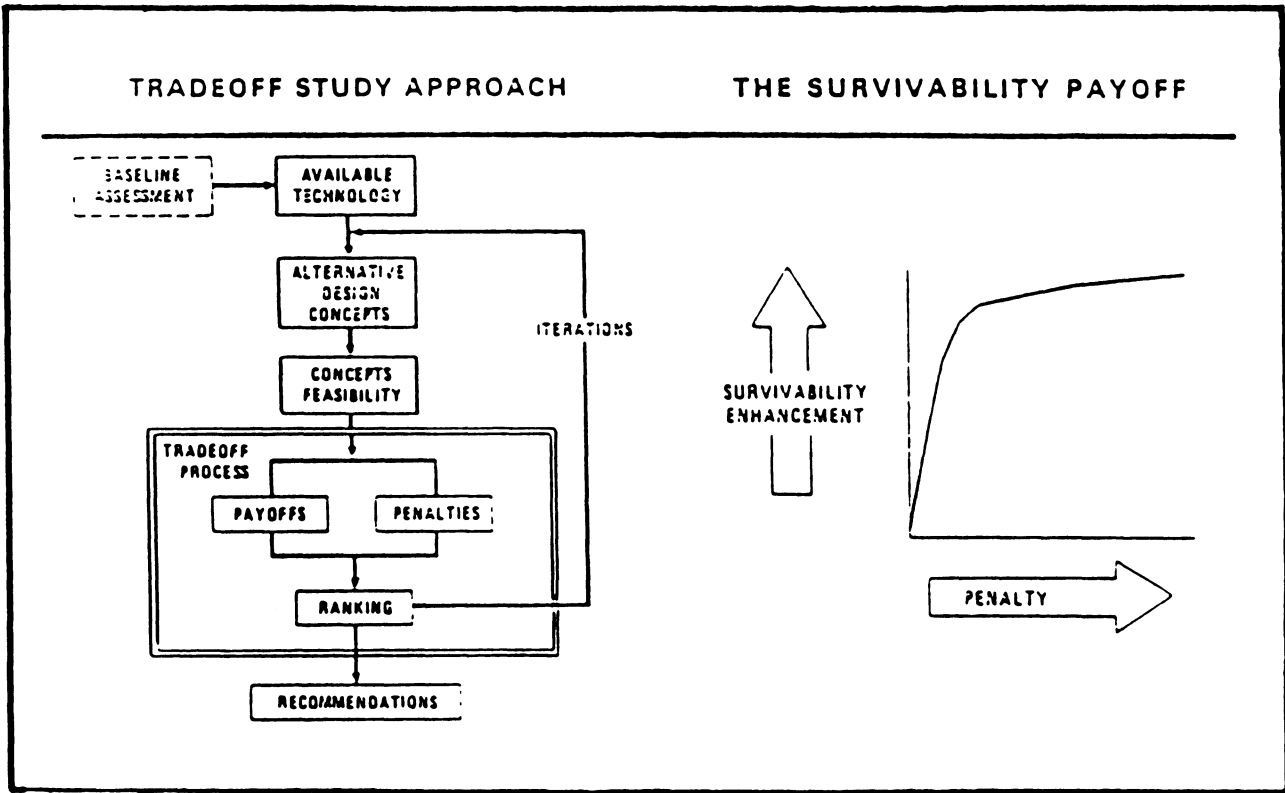
The inputs are

- delta survivability
- delta weight
- delta payload
- delta acquisition cost and
- delta maintenance cost

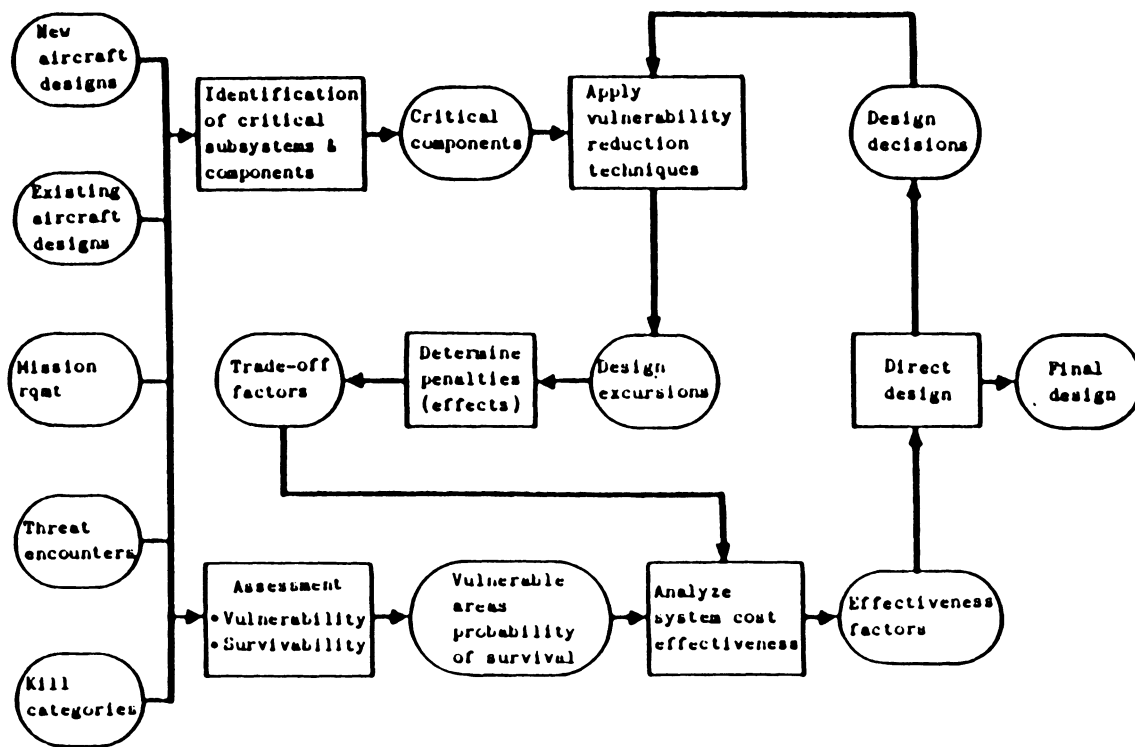


COMBAT AIRCRAFT CONCEPTUAL DESIGN METHODOLOGY

Fig 4.1



Tradeoff Study Approach
Fig 4.2



MIL-HDBK-336-1

Survivability tradeoff studies program.

Fig 4.3

and the outputs of the tradeoff step are

- increase in targets destroyed per aircraft lost
- kills per loss multiplier
- reduction hits on carrier
- decrease in program life cycle cost
- combat value ratio
- cost elasticity of payload delivered to target

The basic question to be answered in the tradeoff analysis is whether or not the modified aircraft is better than the baseline aircraft. To answer this question one must take into account a variety of factors that are indicators of the performance of the aircraft namely, the measures of system effectiveness, which were briefly touched upon in Chapter 3.

The principal objective of the air combat survivability evaluation is the development of a weapon system which derives the maximum payoff in survivability enhancement. Aircraft survivability P_s is not, itself, a measure of effectiveness, but rather a decision variable. The justification for selection and incorporation of a survivability feature into an aircraft system must be proven by an evaluation of its contribution to the effectiveness of the total system. Thus, in assessing one aircraft versus another or the utility of one aircraft modification versus another modification, all decision variables -- P_s , inventory, availability and sortie rate -- must be considered simultaneously such that their interactions are accounted for.

The outputs of the tradeoff analysis are the measures of indicators that helps answer the question regarding the superiority of one aircraft system over another.

The concept of the deltas, which are the inputs to the survivability tradeoff step, was introduced in Chapter 3. The deltas are the total change in a parameter variable due to all the susceptibility/vulnerability reduction techniques. Clearly, the net change is the algebraic sum of the independent changes due to individual susceptibility/vulnerability reduction measures. To illustrate the concept of the deltas consider the delta survivability. Survivability is enhanced by 1. vulnerability reduction and 2. susceptibility reduction. Thus delta survivability is the sum of the delta survivability due to vulnerability reduction (DSVR) and the delta survivability due to susceptibility reduction (DSSR). If S_B be the survivability of the baseline aircraft, S_M the survivability of the modified aircraft, S_{MVR} and S_{MSR} the survivability of the modified aircraft due to vulnerability reduction and susceptibility reduction respectively,

$$S_M - S_B = S_{MVR} - S_B + S_{MSR} - S_B$$

$$\text{or } S_B - S_M = S_B - S_{MVR} + S_B - S_{MSR}$$

$$\text{and } (S_B - S_M)/S_B = (S_B - S_{MVR})/S_B + (S_B - S_{MSR})/S_B$$

$$\text{Therefore } DS = DSVR + DSSR$$

$$\text{where } DS = (S_B - S_M)/S_B = (1 - S_M/S_B)$$

By delta it is meant the change or difference between the baseline and modified with respect to the baseline.

Thus in a similar manner the relationship between the modified and baseline parameters of the inputs to the survivability tradeoff step can be expressed as in Table 4.1

Table 4.1 Survivability Tradeoff Inputs

| Parameter | Delta | Baseline | Modified | Relationship |
|------------------|-------|----------|----------|---------------|
| Survivability | DS | SB | SM | $SM=SB(1-DS)$ |
| Weight | DW | WB | WM | $WM=WB(1-DW)$ |
| Acquisition Cost | DA | AB | AM | $AM=AB(1-DA)$ |
| Maintenance Cost | DM | MB | MM | $MM=MB(1-DM)$ |

In this chapter, the general theory of SURMAN's tradeoff methodology is explained first. Then specific cases -- those pertaining to different types of missions -- are discussed which is followed by the section on incorporation of the deltas into the tradeoff methodology. Next, the models for each type of mission are discussed. Finally, these are all combined and put together to obtain the "encapsulated nomograph" to aid survivability tradeoff analysis.

4.2 THEORY OF SURMAN'S SUSCEPTIBILITY/VULNERABILITY TRADEOFF METHODOLOGY

The attrition model employed in this research is described in this section and the measures of effectiveness to be employed for each type of mission are developed herein.

The rate of change of inventory of a particular force is directly proportional to the product of the strength of the enemy force and its killing power, and it is also proportional to the product of its own strength and its rate of loss to enemy surface threats.

If B_t = inventory of baseline aircraft at time t

M_t = inventory of modified aircraft at time t

b = rate of kill of "M" by "B" (effectiveness of baseline)

c = rate of kill of "B" by "M" (effectiveness of modified)

r_1 = rate of loss of "M" vs surface threats

r_2 = rate of loss of "B" vs surface threats

The model can then be expressed mathematically as

$$\frac{dM_t}{dt} = -bB_t - r_1M_t \quad (4.1)$$

$$\text{and } \frac{dB_t}{dt} = -cM_t - r_2B_t \quad (4.2)$$

The kill rate of a force depends upon the sortie rate of its aircrafts, their availability, the survivability of the aircraft versus airborne threats of the enemy force, and the fraction of the sorties carried out against airborne threat. Thus,

$$b = SRB*AB*(1-SMA)*FSBAT \quad (4.3)$$

$$\text{and } c = SRM*AM*(1-SBA)*FSMAT \quad (4.4)$$

where SRB = sortie rate of Baseline aircraft

SRM = sortie rate of Modified aircraft

AB = availability of Baseline aircraft

AM = availability of Modified aircraft

SBA = survivability of Baseline versus airborne threat

SMA = survivability of Modified versus airborne threat

FSBAT = fraction sorties of Baseline versus airborne threat

FSMAT = fraction sorties of Modified versus airborne threat

$$\text{Also, } r_1 = SRB*AM*(1-SMS)*FSMST \quad (4.5)$$

$$\text{and } r_2 = SRM*AB*(1-SBS)*FSBST \quad (4.6)$$

where SBS = survivability of baseline aircraft vs surface threats

SMS = survivability of modified aircraft vs surface threats

FSBST = fraction sorties of baseline aircraft vs surface threats

FSMST = fraction sorties of modified aircraft vs surface threats

The detailed solution of this system of equations is presented in Appendix A. The solution to the differential equations is

$$M_t = \{ bB_0 (e^{\lambda_2 t} - e^{\lambda_1 t}) + M_0 [(r_1 + \lambda_1) e^{\lambda_2 t} - (r_1 + \lambda_2) e^{\lambda_1 t}] \} / (\lambda_1 - \lambda_2) \quad (4.7)$$

$$B_t = \left\{ -\left(\frac{M_0}{b}\right)(r_1 + \lambda_1)(r_1 + \lambda_2) \left(e^{\lambda_2 t} - e^{\lambda_1 t} \right) \right. \\ \left. B_0 \left[(\lambda_1 + r_1) e^{\lambda_1 t} - (r_1 + \lambda_2) e^{\lambda_2 t} \right] \right\} / (\lambda_1 - \lambda_2) \quad (4.8)$$

$$\text{where } \lambda_1 = \left[-(r_1 + r_2) + \sqrt{(r_1 - r_2)^2 + 4bc} \right] / 2 \quad (4.9)$$

$$\lambda_2 = \left[-(r_1 + r_2) - \sqrt{(r_1 - r_2)^2 + 4bc} \right] / 2 \quad (4.10)$$

This set of equations forms the basis of the analytical solution to the attrition model presented in Chapter 3. Next, the two special cases of this attrition model, namely those pertaining to the attack aircraft and the fighter aircraft are discussed and appropriate measures of efficiency developed.

4.3 ATTRITION FORMULATION FOR ATTACK AIRCRAFT

The primary targets of the attack aircraft are on the surface. The role of the attack aircraft is thus to destroy as many surface targets as possible. The attack aircraft do not engage in an air-to-air combat with the enemy by choice and so it is assumed, for simplicity, that the only threats to the attack aircrafts are surface based. Hence there are no sorties launched by attack aircraft to combat air threats and all the sorties are against surface threats. Thus, using the same terminology as in the general case this special case has

$$FSBAT = FSMAT = 0$$

$$b = c = 0 \quad \text{and}$$

$$FSBST = FSMST = 1$$

substituting in equations 4.9 and 4.10 we obtain

$$\lambda_1 = -r_2 \quad \text{and} \quad \lambda_1 = -r_1$$

Therefore it follows, from equations 4.7 and 4.8, that

$$M_t = M_0 e^{-r_1 t} \quad (4.11)$$

$$\text{and } B_t = B_0 e^{-r_2 t} \quad (4.12)$$

The attrition rates of the baseline attack aircraft (ARB) and the modified attack (ARM) can then be expressed as

$$ARB_t = SRB * AB * (1 - SBS) * B_t = r_2 B_t \quad (4.13)$$

$$ARM_t = SRM * AM * (1 - SMS) * M_t = r_1 M_t \quad (4.14)$$

integrating the attrition rates over the time period yields the cumulative losses of each aircraft. Thus if CLB and CLM denote the cumulative losses of the baseline and modified aircraft respectively, then

$$CLB_t = \int_0^t ARB_t dt = B_0 (1 - e^{-r_2 t}) \quad (4.15)$$

$$\text{and } CLM_t = \int_0^t ARM_t dt = M_0 (1 - e^{-r_1 t}) \quad (4.16)$$

The payload delivered to target is a product of the sortie rate, availability, payload, and the number of the aircraft. If PB and PM represent the payloads of the baseline and modified aircrafts, then we can express the payloads delivered to target by the baseline (PDTB) and modified (PDTM) aircrafts as

$$PDTB_t = SRB * AB * PB * B_t \quad (4.17)$$

$$\text{and } PDTM_t = SRM * AM * PM * M_t \quad (4.18)$$

The cumulative payloads delivered to target by the baseline (CPDTB) and the modified (CPDTM) aircrafts can be obtained by integrating the PDTB and PDTM respectively. Thus

$$CPDTB_t = \int_0^t PDTB_t dt = B_0 (1 - e^{-r_2 t}) PB / (1 - SBS) \quad (4.19)$$

$$\text{and } CPDTM_t = \int_0^t PDTM_t dt = M_0 (1 - e^{-r_1 t}) PM / (1 - SMS) \quad (4.20)$$

Payload delivered to target per aircraft lost can then be obtained by dividing CPDTB by CLB for the baseline aircraft (PDTPBL) and CPDTM by CLM for the modified aircraft (PDTPML). So

$$PDTPBL_t = CPDTB_t / CLB_t = PB / (1 - SBS) \quad (4.21)$$

$$\text{and } PDTPML_t = CPDTM_t / CLM_t = PM / (1 - SMS) \quad (4.22)$$

The increase in payload delivered to target per aircraft lost (IPDTPL) can then be obtained as

$$IPDTPL = (PDTPML - PDTPBL) / PDTPBL \quad (4.23)$$

The increased (life-cycle) cost per aircraft (ICPA) can be expressed in terms of the life cycle cost of the baseline (LCCB) and modified (LCCM) aircrafts as

$$ICPA = (LCCM - LCCB) / LCCB \quad (4.24)$$

It can be said that the modified aircraft is better if $IPDTPL > ICPA$. Expressed as cost elasticity of target destroyed per loss (CETDPL),

$$CETDPL = IPDTPL / ICPA \quad (4.25)$$

and the modified aircraft is better if $CETDPL > 1$.

A model for the attrition formulation of attack aircraft, based on the discussions presented in this section, is presented next. This model is used to perform the tradeoff analysis also. In the model the generic U.S. combat attack aircraft is used and its attrition versus surface threats studied. By performing two simulation runs the modified and the baseline aircraft can be compared. In the baseline case all the deltas would be zero while the result of the modifications would be reflected in the deltas for the modified case. The influence of various types of modifications can also be studied using reruns with the appropriate changes in the delta values. The actual tradeoff analysis is described

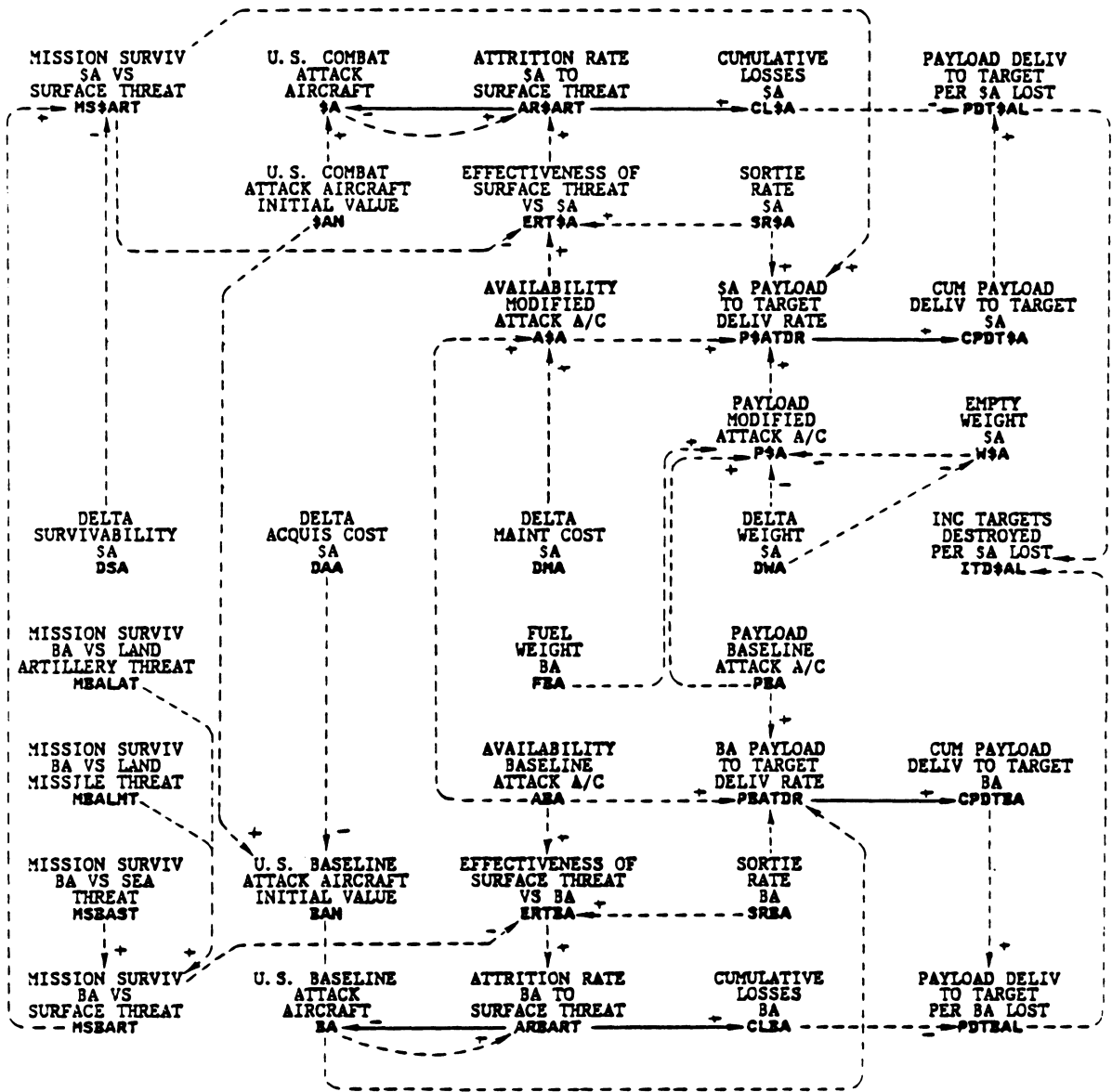
later on in this chapter. The causal diagram, system equations and the results of the computer simulation are shown in Figures 4.4, 4.5 and 4.6 respectively.

In the model shown, \$A represents the modified aircraft. This is indicated by the values of the deltas being different from zero. In the simulation results it is interesting to note that the attrition rate of \$A (AR\$ART) is much smaller than that of BA (ARBART) in the beginning.

As a result, even though the initial inventory of \$A is less than that of BA, it is the BA inventory that is completely depleted first. The decrease in the attrition rate can be attributed to the changes (deltas) made in the survivability versus surface threats (DSA) the other deltas such as delta acquisition cost, delta maintenance cost and delta weight also influence ITD\$AL through intermediate variables such as the availability of \$A (A\$A), the initial inventory, ITD\$AL ($=0.9634 > 0$) indicates that the \$A is better than the baseline aircraft.

4.4 ATTRITION FORMULATION FOR FIGHTER AIRCRAFT

The primary role of fighter aircraft is to establish air superiority by engaging in air-to-air combat with the enemy air threats. Thus the targets of the fighter aircraft are airborne and so are its threats. Fighter aircraft do not usually carry out sorties against surface threats, and their sorties are primarily versus airborne threat. Also, there is assumed to be no threat to the fighter aircraft from the surface. Thus,



CAUSAL DIAGRAM FOR SURVIVABILITY SUBMODEL - ATTACK AIRCRAFT

Fig 4.4

```

* JTCG/AS SURMAN MODEL
NOTE *****
NOTE ***** SURVIVABILITY SUBMODEL *****
NOTE ***** ATTACK AIRCRAFT *****
NOTE ***** ATTRITION FORMULATION *****
NOTE *****
L   $A.K=MAX(0,$A.J-(DT)(AR$ART.JK))
N   $A=$AN
NOTE $A - ATA INVENTORY (AIRCRAFT)
C   $AN=810
NOTE $AN - ATA INITIAL INVENTORY (AIRCRAFT)
R   AR$ART.KL=$A.K*ERT$A.K
NOTE AR$ART - ATTRITION RATE OF $A VS SURF THREATS (AIRCRAFT/DAY)
A   ERT$A.K=SR$A*$A*(1-MS$ART.K)
NOTE ERT$A - EFFECTIVENESS OF SURFACE THREATS VS $A (NUMBER/DAY)
C   SR$A=4
NOTE SR$A - SORTIE RATE OF $A (NUMBER/DAY)
N   A$A=ABA/(1-DMA)
NOTE A$A - AVAILABILITY OF $A (PROB)
C   ABA=.5
NOTE ABA - AVAILABILITY OF BA - BASELINE ATTACK AIRCRAFT (PROB)
A   MS$ART.K=MSBART*(1-DSA)
NOTE MS$ART - MISSION SURVIVABILITY OF $A VS SURF THREATS (PROB)
L   BA.K=MAX(0,BA.J-(DT)(ARBART.JK))
N   BA=BAN
NOTE BA - BASELINE ATTACK AIRCRAFT (A-6) INVENTORY (AIRCRAFT)
N   BAN=$AN*(1-DAA)
NOTE BAN - BASELINE ATTACK AIRCRAFT INITIAL INVENTORY (AIRCRAFT)
R   ARBART.KL=BA.K*ERTBA
NOTE ARBART - ATTRITION RATE OF BA VS SURF THREATS (AIRCRAFT/DAY)
N   ERTBA=SRBA*ABA*(1-MSBART)
NOTE ERTBA - EFFECTIVENESS OF SURFACE THREATS VS BA (NUMBER/DAY)
N   SRBA=SR$A
NOTE SRBA - SORTIE RATE OF BA (NUMBER/DAY)
NOTE ***** MEASURES OF EFFECTIVENESS *****
A   ITD$AL.K=MAX((PDT$AL.K-PDTBAL.K)/PDTBAL.K,0)
NOTE ITD$AL - INC IN TARGETS DESTROYED PER AIRCRAFT LOST (DIM)
A   PDT$AL.K=MAX(0,CPDT$A.K/CL$A.K)
NOTE PDT$AL - PAYLOAD DELIV TO TARGET PER $A LOST (LBS/AIRCRAFT)
A   PDTBAL.K=MAX(0,CPDTBA.K/CLBA.K)
NOTE PDTBAL - PAYLOAD DELIV TO TARGET PER BA LOST (LBS/AIRCRAFT)
C   O=.00001
NOTE O - CONSTANT USED TO AVOID DIVISION BY ZERO (DIM)
L   CPDT$A.K=CPDT$A.J+(DT)(P$ATDR.JK)
N   CPDT$A=0
NOTE CPDT$A - CUMULATIVE PAYLOAD DELIVERED TO TARGET BY $A (LBS)
L   CL$A.K=CL$A.J+(DT)(AR$ART.JK)
N   CL$A=0
NOTE CL$A - CUMULATIVE LOSSES OF $A (AIRCRAFT)

```

Fig 4.5 System Equations for Attrition Formulation - Attack Aircraft

```

L   CPDTBA.K=CPDTBA.J+(DT)(PBATDR.JK)
N   CPDTBA=0
NOTE CPDTBA - CUMULATIVE PAYLOAD DELIVERED TO TARGET BY BA (LBS)
L   CLBA.K=CLBA.J+(DT)(ARBART.JK)
N   CLBA=.001
NOTE CLBA - CUMULATIVE LOSSES OF BA (AIRCRAFT)
R   P$ATDR.KL=$A.K*SR$A*A$A*P$A
NOTE P$ATDR - PAYLOAD OF $A TO TARGET DELIVERY RATE (LBS/DAY)
R   PBATDR.KL=BA.K*SRBA*ABA*PBA
NOTE PBATDR - PAYLOAD OF BA TO TARGET DELIVERY RATE (LBS/DAY)
N   P$A=(((WBA+PBA+FBA-W$A)/FBA)*(2*WBA+PBA))-2*W$A)/
X   (1+((2*WBA+PBA)/FBA))
NOTE P$A - PAYLOAD OF $A (LBS)
N   W$A=WBA*(1-DWA)
NOTE W$A - EMPTY WEIGHT OF $A (LBS)
C   WBA=26000
NOTE WBA - EMPTY WEIGHT OF BASELINE AIRCRAFT, BA (LBS)
C   PBA=18000
NOTE PBA - PAYLOAD OF BASELINE AIRCRAFT (LBS)
C   FBA=16000
NOTE FBA - FUEL WEIGHT OF BASELINE AIRCRAFT, BA (LBS)
NOTE ***** INPUTS FROM SURVIVABILITY ASSESSMENT *****
C   MSBART=.96
NOTE MSBART - MISSION SURVIVABILITY OF BA VS SURF THREATS (PROB)
C   DSA=-.0175
NOTE DSA - DELTA SURVIVABILITY OF ATTACK AIRCRAFT (DIM)
C   DAA=-.93
NOTE DAA - DELTA ACQUISITION COST OF ATTACK AIRCRAFT (DIM)
C   DMA=0
NOTE DMA - DELTA MAINTENANCE COST OF ATTACK AIRCRAFT (DIM)
C   DWA=.081
NOTE DWA - DELTA WEIGHT OF ATTACK AIRCRAFT (DIM)
NOTE ***** OUTPUT SPECIFICATION *****
SPEC DT=.5/LENGTH=100/PLTPER=5/PRTPER=5
PRINT $A,AR$ART,BA,ARBART
PRINT ITD$AL,PDT$AL,PDTBAL,CPDT$A,CPDTBA
PRINT CL$A,CLBA,P$ATDR,PBATDR
PLOT $A=$,BA=B(0,1600)
PLOT CL$A=M,CLBA=0
PLOT $A=$,BA=B,CL$A=M,CLBA=0
RUN
QUIT

```

Fig 4.5 (cont.)

Fig 4.6 Simulation Results - Attrition Formulation of Attack Aircraft

| | | | | | |
|----------|-------|----------------|----------------|----------------|---------------|
| TIME= | .0 | SA= 810.0 | AR\$ART= 37.58 | BA= 1563. | ARBART= 125.1 |
| ITD\$AL= | .0000 | PDT\$AL= .0 | PDTBAL= .0 | CPDT\$A= .0 | CPDTBA= .0 |
| CL\$A= | .0 | CLBA= 0. | P\$ATDR=33.21M | PBATDR=56.28M | CETDPL= .000 |
| ----- | | | | | |
| TIME= | 5.0 | SA= 640.5 | AR\$ART= 29.72 | BA= 1039. | ARBART= 83.1 |
| ITD\$AL= | .9634 | PDT\$AL=883.5T | PDTBAL=450.0T | CPDT\$A=149.7M | CPDTBA=235.8M |
| CL\$A= | 169.5 | CLBA= 524. | P\$ATDR=26.26M | PBATDR=37.42M | CETDPL= 1.036 |
| ----- | | | | | |
| TIME= | 10.0 | SA= 506.5 | AR\$ART= 23.50 | BA= 691. | ARBART= 55.3 |
| ITD\$AL= | .9634 | PDT\$AL=883.5T | PDTBAL=450.0T | CPDT\$A=268.1M | CPDTBA=392.5M |
| CL\$A= | 303.5 | CLBA= 872. | P\$ATDR=20.76M | PBATDR=24.88M | CETDPL= 1.036 |
| ----- | | | | | |
| TIME= | 15.0 | SA= 400.5 | AR\$ART= 18.59 | BA= 459. | ARBART= 36.8 |
| ITD\$AL= | .9634 | PDT\$AL=883.5T | PDTBAL=450.0T | CPDT\$A=361.8M | CPDTBA=496.8M |
| CL\$A= | 409.5 | CLBA= 1104. | P\$ATDR=16.42M | PBATDR=16.54M | CETDPL= 1.036 |
| ----- | | | | | |
| TIME= | 20.0 | SA= 316.7 | AR\$ART= 14.70 | BA= 305. | ARBART= 24.4 |
| ITD\$AL= | .9634 | PDT\$AL=883.5T | PDTBAL=450.0T | CPDT\$A=435.8M | CPDTBA=566.0M |
| CL\$A= | 493.3 | CLBA= 1258. | P\$ATDR=12.98M | PBATDR=10.99M | CETDPL= 1.036 |
| ----- | | | | | |
| TIME= | 25.0 | SA= 250.5 | AR\$ART= 11.62 | BA= 203. | ARBART= 16.2 |
| ITD\$AL= | .9634 | PDT\$AL=883.5T | PDTBAL=450.0T | CPDT\$A=494.3M | CPDTBA=612.1M |
| CL\$A= | 559.5 | CLBA= 1360. | P\$ATDR=10.27M | PBATDR= 7.31M | CETDPL= 1.036 |
| ----- | | | | | |
| TIME= | 30.0 | SA= 198.1 | AR\$ART= 9.19 | BA= 135. | ARBART= 10.8 |
| ITD\$AL= | .9634 | PDT\$AL=883.5T | PDTBAL=450.0T | CPDT\$A=540.6M | CPDTBA=642.7M |
| CL\$A= | 611.9 | CLBA= 1428. | P\$ATDR= 8.12M | PBATDR= 4.86M | CETDPL= 1.036 |
| ----- | | | | | |
| TIME= | 35.0 | SA= 156.6 | AR\$ART= 7.27 | BA= 90. | ARBART= 7.2 |
| ITD\$AL= | .9634 | PDT\$AL=883.5T | PDTBAL=450.0T | CPDT\$A=577.3M | CPDTBA=663.1M |
| CL\$A= | 653.4 | CLBA= 1474. | P\$ATDR= 6.42M | PBATDR= 3.23M | CETDPL= 1.036 |
| ----- | | | | | |
| TIME= | 40.0 | SA= 123.9 | AR\$ART= 5.75 | BA= 60. | ARBART= 4.8 |
| ITD\$AL= | .9634 | PDT\$AL=883.5T | PDTBAL=450.0T | CPDT\$A=606.2M | CPDTBA=676.6M |
| CL\$A= | 686.1 | CLBA= 1504. | P\$ATDR= 5.08M | PBATDR= 2.15M | CETDPL= 1.036 |
| ----- | | | | | |
| TIME= | 45.0 | SA= 97.9 | AR\$ART= 4.54 | BA= 40. | ARBART= 3.2 |
| ITD\$AL= | .9634 | PDT\$AL=883.5T | PDTBAL=450.0T | CPDT\$A=629.1M | CPDTBA=685.6M |
| CL\$A= | 712.0 | CLBA= 1524. | P\$ATDR= 4.02M | PBATDR= 1.43M | CETDPL= 1.036 |
| ----- | | | | | |
| TIME= | 50.0 | SA= 77.5 | AR\$ART= 3.59 | BA= 26. | ARBART= 2.1 |
| ITD\$AL= | .9634 | PDT\$AL=883.5T | PDTBAL=450.0T | CPDT\$A=647.2M | CPDTBA=691.6M |
| CL\$A= | 732.5 | CLBA= 1537. | P\$ATDR= 3.18M | PBATDR= .95M | CETDPL= 1.036 |
| ----- | | | | | |

Fig 4.6 Simulation Results - Attrition Formulation of Attack Aircraft

| | | | | | | | | | |
|----------|-------|----------|--------|----------|--------|----------|--------|---------|--------|
| TIME= | 55.0 | \$A= | 61.2 | AR\$ART= | 2.84 | BA= | 18. | ARBART= | 1.4 |
| ITD\$AL= | .9634 | PDT\$AL= | 883.5T | PDTBAL= | 450.0T | CPDT\$A= | 661.5M | CPDTBA= | 695.6M |
| CL\$A= | 748.7 | CLBA= | 1546. | P\$ATDR= | 2.51M | PBATDR= | .63M | CETDPL= | 1.036 |
| ----- | | | | | | | | | |
| TIME= | 60.0 | \$A= | 48.4 | AR\$ART= | 2.25 | BA= | 12. | ARBART= | .9 |
| ITD\$AL= | .9634 | PDT\$AL= | 883.5T | PDTBAL= | 450.0T | CPDT\$A= | 672.8M | CPDTBA= | 698.2M |
| CL\$A= | 761.5 | CLBA= | 1552. | P\$ATDR= | 1.99M | PBATDR= | .42M | CETDPL= | 1.036 |
| ----- | | | | | | | | | |
| TIME= | 65.0 | \$A= | 38.3 | AR\$ART= | 1.78 | BA= | 8. | ARBART= | .6 |
| ITD\$AL= | .9634 | PDT\$AL= | 883.5T | PDTBAL= | 450.0T | CPDT\$A= | 681.8M | CPDTBA= | 700.0M |
| CL\$A= | 771.7 | CLBA= | 1556. | P\$ATDR= | 1.57M | PBATDR= | .28M | CETDPL= | 1.036 |
| ----- | | | | | | | | | |
| TIME= | 70.0 | \$A= | 30.3 | AR\$ART= | 1.41 | BA= | 5. | ARBART= | .4 |
| ITD\$AL= | .9634 | PDT\$AL= | 883.5T | PDTBAL= | 450.0T | CPDT\$A= | 688.9M | CPDTBA= | 701.1M |
| CL\$A= | 779.7 | CLBA= | 1558. | P\$ATDR= | 1.24M | PBATDR= | .19M | CETDPL= | 1.036 |
| ----- | | | | | | | | | |
| TIME= | 75.0 | \$A= | 24.0 | AR\$ART= | 1.11 | BA= | 3. | ARBART= | .3 |
| ITD\$AL= | .9634 | PDT\$AL= | 883.5T | PDTBAL= | 450.0T | CPDT\$A= | 694.5M | CPDTBA= | 701.9M |
| CL\$A= | 786.0 | CLBA= | 1560. | P\$ATDR= | .98M | PBATDR= | .12M | CETDPL= | 1.036 |
| ----- | | | | | | | | | |
| TIME= | 80.0 | \$A= | 18.9 | AR\$ART= | .88 | BA= | 2. | ARBART= | .2 |
| ITD\$AL= | .9634 | PDT\$AL= | 883.5T | PDTBAL= | 450.0T | CPDT\$A= | 698.9M | CPDTBA= | 702.4M |
| CL\$A= | 791.0 | CLBA= | 1561. | P\$ATDR= | .78M | PBATDR= | .08M | CETDPL= | 1.036 |
| ----- | | | | | | | | | |
| TIME= | 85.0 | \$A= | 15.0 | AR\$ART= | .69 | BA= | 2. | ARBART= | .1 |
| ITD\$AL= | .9634 | PDT\$AL= | 883.5T | PDTBAL= | 450.0T | CPDT\$A= | 702.4M | CPDTBA= | 702.8M |
| CL\$A= | 795.0 | CLBA= | 1562. | P\$ATDR= | .61M | PBATDR= | .05M | CETDPL= | 1.036 |
| ----- | | | | | | | | | |
| TIME= | 90.0 | \$A= | 11.8 | AR\$ART= | .55 | BA= | 1. | ARBART= | .1 |
| ITD\$AL= | .9634 | PDT\$AL= | 883.5T | PDTBAL= | 450.0T | CPDT\$A= | 705.2M | CPDTBA= | 703.0M |
| CL\$A= | 798.1 | CLBA= | 1562. | P\$ATDR= | .49M | PBATDR= | .04M | CETDPL= | 1.036 |
| ----- | | | | | | | | | |
| TIME= | 95.0 | \$A= | 9.4 | AR\$ART= | .43 | BA= | 1. | ARBART= | .1 |
| ITD\$AL= | .9634 | PDT\$AL= | 883.5T | PDTBAL= | 450.0T | CPDT\$A= | 707.3M | CPDTBA= | 703.2M |
| CL\$A= | 800.6 | CLBA= | 1563. | P\$ATDR= | .38M | PBATDR= | .02M | CETDPL= | 1.036 |
| ----- | | | | | | | | | |
| TIME= | 100.0 | \$A= | 7.4 | AR\$ART= | .34 | BA= | 0. | ARBART= | .0 |
| ITD\$AL= | .9634 | PDT\$AL= | 883.5T | PDTBAL= | 450.0T | CPDT\$A= | 709.1M | CPDTBA= | 703.3M |
| CL\$A= | 802.6 | CLBA= | 1563. | P\$ATDR= | .30M | PBATDR= | .02M | CETDPL= | 1.036 |
| ----- | | | | | | | | | |

Fig 4.6 (cont)

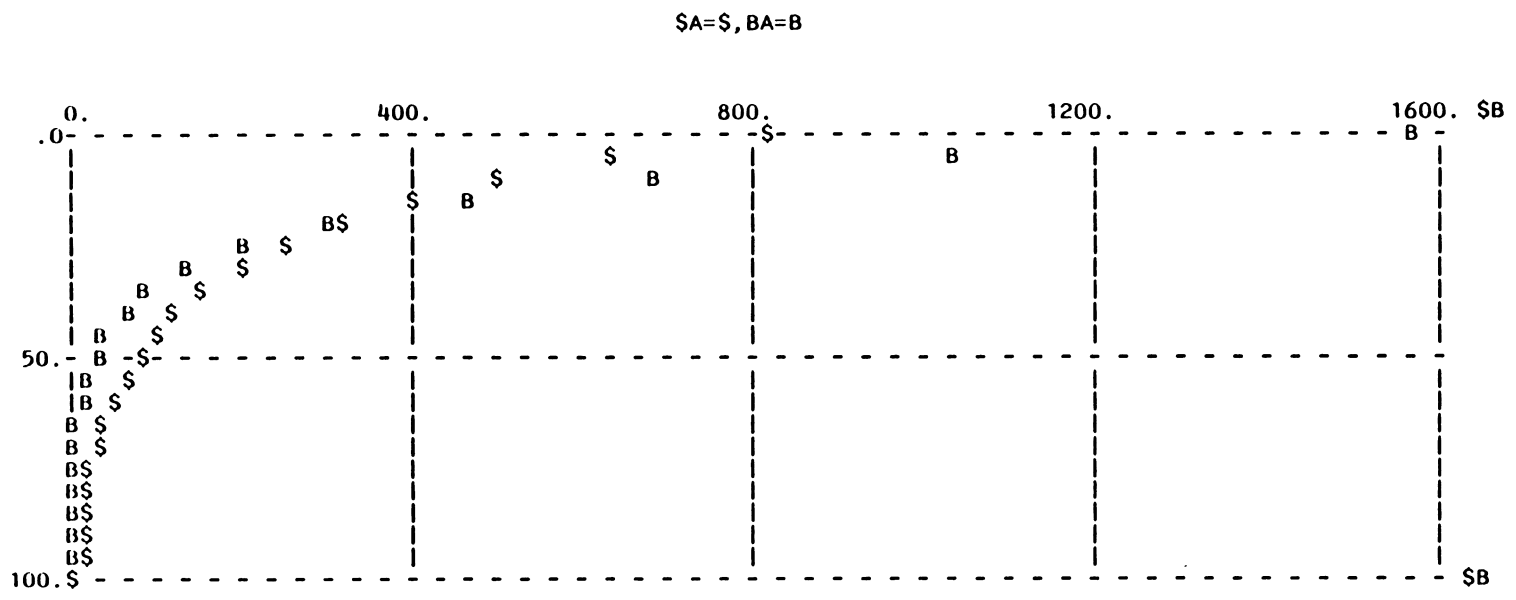


Fig 4.6 (cont.)

the air-to-air combat role of the fighter aircraft can be closely approximated by a special case of the general attrition model discussed in Section 4.2. Using the same terminology, in this case we have

$$FSBST = FSMST = 0$$

$$r_1 = r_2 = 0 \quad \text{and}$$

$$FSBAT = FSMAT = 1$$

substituting in equations 4.9 and 4.10 we obtain

$$\lambda_1 = \sqrt{bc} \quad \text{and} \quad \lambda_2 = -\sqrt{bc}$$

Equations 4.7 and 4.8 can then be simplified to get

$$\begin{aligned} M_t &= \{bB_0(e^{\lambda_2 t} - e^{\lambda_1 t}) + M_0(\lambda_1 e^{\lambda_2 t} - \lambda_2 e^{\lambda_1 t})\} / (\lambda_1 - \lambda_2) \\ &= \{bB_0(e^{\sqrt{bc}t} - e^{-\sqrt{bc}t}) - M_0\sqrt{bc}(e^{\sqrt{bc}t} + e^{-\sqrt{bc}t})\} / (-\sqrt{bc}) \\ M_t &= M_0 \cosh\sqrt{bc} t - B_0\sqrt{b/c} \sinh\sqrt{bc} t \end{aligned} \quad (4.26)$$

and similarly

$$B_t = B_0 \cosh\sqrt{bc} t - M_0\sqrt{c/b} \sinh\sqrt{bc} t \quad (4.27)$$

Combat value ratio (COMVR) is now defined as the fighting strength of the modified aircraft force divided by the fighting strength of the baseline aircraft force (as was mentioned in the discussion on the survivability submodel in Chapter 3). Assuming that the weaker side is annihilated at time t . We have the following

1. $B_t = M_t = 0$

from equations 4.26 and 4.27,

$$COMVR = \coth\sqrt{bc} t = (B_0/M_0)\sqrt{b/c} = (M_0/B_0)\sqrt{c/b} = 1.0 \quad (4.28)$$

2. $B_t = 0$, i.e., when the modified is better.

from equation 4.27,

$$\text{COMVR} = \coth \sqrt{bc} \, t = (M_0/B_0) \sqrt{c/b} > 1.0 \quad (4.29)$$

Another measure of effectiveness that developed is the decreased program life cycle cost, DPLCC. DPLCC is defined as the "delta" program life cycle cost and

$$\text{DPLCC} = (\text{PCB}_t * \text{FFLB}_t - \text{PCM}_t * \text{FFLM}_t) / (\text{PCB}_t * \text{FFLM}_t) \quad (4.30)$$

where PCB = program cost for baseline aircraft

PCM = program cost for modified aircraft

FFLB = fraction force lcost for baseline aircraft

FFLM = fraction force lcost for modified aircraft

for $\text{PCB}_t = \text{PCM}_t$,

$$\text{DPLCC} = 1 - (\text{FFLM}_t / \text{FFLB}_t) \quad (4.31)$$

But, $\text{FFLM}_t = 1 - (M_t/M_0) = (M_0 - M_t)/M_0$

and $\text{FFLB}_t = 1 - (B_t/B_0) = (B_0 - B_t)/B_0$

substituting in equation 4.31 yields

$$\text{DPLCC} = (B_0 M_t - M_0 B_t) / [M_0 (B_0 - B_t)] \quad (4.32)$$

for the modified force to be better, $B_t = 0$ and thus

$$\text{DPLCC} = M_t / M_0 \quad (4.33)$$

We have already established that $\text{COMVR} = \coth \sqrt{bc} \, t$. Then the time at which the weaker side is annihilated is given by,

$$t = (\coth^{-1} \text{COMVR}) / \sqrt{bc} \quad (4.34)$$

Substituting in equation 4.26 for M_t and using it in equation 4.33 results in

$$\text{DPLCC}_t = \cosh(\coth^{-1} \text{COMVR}) - [\sinh(\coth^{-1} \text{COMVR})] / \text{COMVR} \quad (4.35)$$

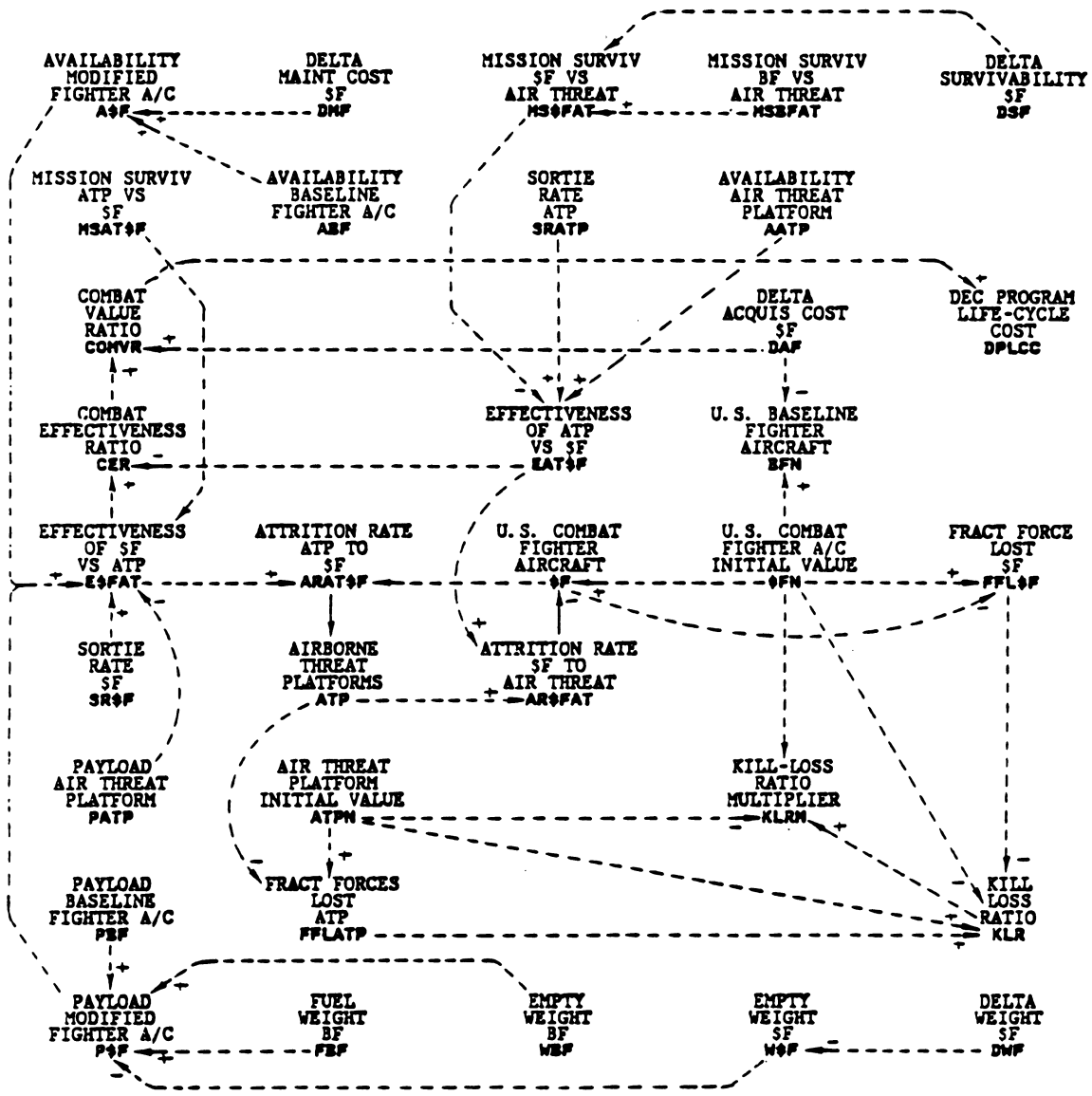
and obviously, for the modified aircraft to be better DPLCC must be greater than zero,

i.e., $DPLCC > 0$ if modified aircraft is better.

A model for the attrition formulation for fighter aircraft is presented next. The model is based upon the discussion presented earlier in this section. The model compares the performance of the modified U.S. fighter aircraft (\$F) versus the Airborne Threat Platforms (ATP). The causal relationships amongst the variables and parameters is captured in Figure 4.7. The system equations, in DYNAMO, are presented in Figure 4.8 and Figure 4.9 presents the results of the computer simulation.

In the model the generic U.S. fighter aircraft is attrited directly by the air threat platforms and vice versa. So this is to determine the air superiority. In order to perform a tradeoff analysis, the performance of each type of aircraft can be simulated and compared with one another. The baseline aircraft would have all the deltas to be zero while the deltas for the modified aircraft would reflect the changes made. However, in the tradeoff analysis described later in this chapter a slightly different approach is used. The example model presented here is for the case of a modified aircraft

Once again, it is interesting to note in the results of the simulation that while the initial inventory of \$F is less than that of ATP, it is the ATP inventory that gets reduced first. This speaks of the effectiveness and superiority of the SF over ATP and is reflected in the measures of effectiveness such as the combat value ratio ($COMVR = 1.703 > 1.0$), decreased program life cycle cost ($DPLCC = 0.5439 > 0$) and the



CAUSAL DIAGRAM FOR SURVIVABILITY SUBMODEL - FIGHTER AIRCRAFT

Fig 4.7

* JTCG/AS SURMAN MODEL

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NOTE *****
NOTE ***** SURVIVABILITY SUBMODEL *****
NOTE ***** FIGHTER AIRCRAFT *****
NOTE ***** ATTRITION FORMULATION *****
NOTE *****
L   $F.K=$F.J-(DT)(AR$FAT.JK)
N   $F=$FN
NOTE $F - U.S. MODIFIED FIGHTER AIRCRAFT INVENTORY (AIRCRAFT)
C   $FN=540
NOTE $FN - $F AIRCRAFT INITIAL INVENTORY (AIRCRAFT)
R   AR$FAT.KL=CLIP(ATP.K*EAT$F.K,O,ATP.K,O)
NOTE AR$FAT - ATTRITION RATE OF $F VS AIR THREATS (AIRCRAFT/DAY)
C   O=.01
NOTE O - SMALL NUMBER TO AVOID DIVISION BY ZERO
A   EAT$F.K=SRATP*AATP*(1-MS$FAT.K)
NOTE EAT$F - EFFECTIVENESS OF AIR THREATS VS $F (NUMBER/DAY)
C   SRATP=4
NOTE SRATP - SORTIE RATE OF ATP (NUMBER/DAY)
C   AATP=.5
NOTE AATP - AVAILABILITY OF ATP (PROB)
A   MS$FAT.K=MSBFAT*(1-DSF)
NOTE MS$FAT - MISSION SURVIVABILITY OF $F VS AIR THREATS (PROB)
L   ATP.K=MAX(0,ATP.J-(DT)(ARAT$F.JK))
N   ATP=ATPN
NOTE ATP - AIR THREAT PLATFORM INVENTORY (PLATFORM)
C   ATPN=1080
NOTE ATPN - AIR THREAT PLATFORM INITIAL INVENTORY (PLATFORM)
R   ARAT$F.KL=CLIP($F.K*E$FAT.K,O,$F.K,O)
NOTE ARAT$F - ATTRITION RATE OF ATP VS $F (PLATFORM/DAY)
A   E$FAT.K=SR$F*A$F*(1-MSAT$F.K)*(P$F/PATP)
NOTE ERTBA - EFFECTIVENESS OF $F VS ATP (NUMBER/DAY)
N   SR$F=4
NOTE SR$F - SORTIE RATE OF $F (NUMBER/DAY)
N   A$F=ABF/(1-DMF)
NOTE A$F - AVAILABILITY OF $F (PROB)
C   ABF=.5
NOTE ABF - AVAILABILITY OF BF (PROB)
A   MSAT$F.K=MSATBF
NOTE MSAT$F - MISSION SURVIVABILITY OF AT VS $F (PROB)
N   MSATBF=1-(1-MSBFAT)(ATPN/BFN)(ATPN/BFN)(SRATP/SRBF)
X   (AATP/ABF)(PATP/PBF)
NOTE MSATBF - MISSION SURVIVABILITY OF AT VS BF (PROB)
N   SRBF=SR$F
NOTE SRBF - SORTIE RATE OF BF (NUMBER/DAY)
C   PATP=10000
NOTE PATP - PAYLOAD OF ATP (LBS)

```

Fig 4.8 System Equations for Attrition Formulation - Fighter Aircraft

```

N   P$F=(((WBF+PBF+FBF-W$F)/FBF)*(2*WBF+PBF))-2*W$F)/
X   (1+((2*WBF+PBF)/FBF))
NOTE P$F - PAYLOAD OF $F (LBS)
N   W$F=WBF*(1-DWF)
NOTE W$F - EMPTY WEIGHT OF $F (LBS)
C   WBF=40000
NOTE WBF - EMPTY WEIGHT OF BASELINE AIRCRAFT, BF (LBS)
C   PBF=17000
NOTE PBF - PAYLOAD OF BASELINE AIRCRAFT (LBS)
C   FBF=17000
NOTE FBF - FUEL WEIGHT OF BASELINE AIRCRAFT, BF (LBS)
N   BFN=$FN*(1-DAF)
NOTE BFN - INITIAL INVENTORY OF BASELINE FIGHTERS (AIRCRAFT)
NOTE ***** MEASURES OF EFFECTIVENESS *****
A   CER.K=SQRT(E$FAT.K/EAT$F.K)
NOTE CER - COMBAT EFFECTIVENESS RATIO (DIM)
S   COMVR.K=CER.K/(1-DAF)
NOTE COMVR - COMBAT VALUE RATIO (DIM)
S   DPLCC.K=1-(FELSF.K/FLLBF.K)
NOTE DPLCC - DECREASE PROGRAM LIFE-CYCLE COST (DIM)
A   FFLBF.K=FFLATP.K
NOTE FFLBF - FRACTION FORCE LOST BF (DIM)
A   FFLATP.K=CLIP(0,(ATPN-ATP.K)/ATPN,ATP.K,ATPN)
NOTE FFLATP - FRACTION FORCE LOST ATP
A   FFL$F.K=CLIP(0,($FN-$F.K)/$FN,$F.K,$FN)
NOTE FFL$F - FRACTION FORCE LOST $F
A   KLR.K=(FFLATP.K*ATPN)/(FFL$F.K*$FN)
NOTE KLR - KILL LOSS RATIO (DIM)
A   KLRM.K=KLR.K/(ATPN/$FN)
NOTE KLRM - KILL LOSS RATIO MULTIPLIER (DIM)
NOTE ***** INPUTS FROM SURVIVABILITY ASSESSMENT *****
C   MSBFAT=.965
NOTE MSBFAT - MISSION SURVIVABILITY OF BF VS AIR THREATS (PROB)
C   DSF=-.017
NOTE DSF - DELTA SURVIVABILITY OF FIGHTER AIRCRAFT (DIM)
C   DAF=-.33
NOTE DAF - DELTA ACQUISITION COST OF FIGHTER AIRCRAFT (DIM)
C   DMF=0
NOTE DMF - DELTA MAINTENANCE COST OF FIGHTER AIRCRAFT (DIM)
C   DWF=.0761
NOTE DWF - DELTA WEIGHT OF FIGHTER AIRCRAFT (DIM)
NOTE ***** OUTPUT SPECIFICATION *****
SPEC DT=.05/LENGTH=20/PLTPER=1/PRTPER=2
PRINT $F,AR$FAT,EAT$F,ATP
PRINT ARAT$F,E$FAT,MSATBF,PSF,W$F
PRINT CER,COMVR,DPLCC,KLR,KLRM
PRINT FFLBF,FFLATP,FFL$F
PLOT SF=F,ATP=A(0,1200)
RUN

```

Fig 4.8 (cont.)

| | | | | | | |
|----------|-------|--------------|---------------|---------------|-------|--------|
| TIME= | .00 | \$F=540.0 | AR\$FAT=40.17 | EAT\$F=37.19A | ATP= | 1080. |
| ARAT\$F= | 103.1 | E\$FAT=.1909 | MSATBF=.9534 | P\$F= 20.50T | W\$F= | 36.96T |
| CER= | 2.265 | COMVR=1.703 | DPLCC=.0000 | KLR= 2.000 | KLRM= | 1.000 |
| FFLBF= | .010 | FFLATP= .010 | FFL\$F=.0100 | | | |
| ----- | | | | | | |
| TIME= | 2.00 | \$F=466.8 | AR\$FAT=33.02 | EAT\$F=37.19A | ATP= | 888. |
| ARAT\$F= | 89.1 | E\$FAT=.1909 | MSATBF=.9534 | P\$F= 20.50T | W\$F= | 36.96T |
| CER= | 2.265 | COMVR=1.703 | DPLCC=.2377 | KLR= 2.624 | KLRM= | 1.312 |
| FFLBF= | .178 | FFLATP= .178 | FFL\$F=.1356 | | | |
| ----- | | | | | | |
| TIME= | 4.00 | \$F=406.9 | AR\$FAT=26.83 | EAT\$F=37.19A | ATP= | 721. |
| ARAT\$F= | 77.7 | E\$FAT=.1909 | MSATBF=.9534 | P\$F= 20.50T | W\$F= | 36.96T |
| CER= | 2.265 | COMVR=1.703 | DPLCC=.2581 | KLR= 2.696 | KLRM= | 1.348 |
| FFLBF= | .332 | FFLATP= .332 | FFL\$F=.2464 | | | |
| ----- | | | | | | |
| TIME= | 6.00 | \$F=358.7 | AR\$FAT=21.40 | EAT\$F=37.19A | ATP= | 575. |
| ARAT\$F= | 68.5 | E\$FAT=.1909 | MSATBF=.9534 | P\$F= 20.50T | W\$F= | 36.96T |
| CER= | 2.265 | COMVR=1.703 | DPLCC=.2815 | KLR= 2.784 | KLRM= | 1.392 |
| FFLBF= | .467 | FFLATP= .467 | FFL\$F=.3358 | | | |
| ----- | | | | | | |
| TIME= | 8.00 | \$F=320.7 | AR\$FAT=16.58 | EAT\$F=37.19A | ATP= | 446. |
| ARAT\$F= | 61.2 | E\$FAT=.1909 | MSATBF=.9534 | P\$F= 20.50T | W\$F= | 36.96T |
| CER= | 2.265 | COMVR=1.703 | DPLCC=.3084 | KLR= 2.892 | KLRM= | 1.446 |
| FFLBF= | .587 | FFLATP= .587 | FFL\$F=.4062 | | | |
| ----- | | | | | | |
| TIME= | 10.00 | \$F=291.8 | AR\$FAT=12.23 | EAT\$F=37.19A | ATP= | 329. |
| ARAT\$F= | 55.7 | E\$FAT=.1909 | MSATBF=.9534 | P\$F= 20.50T | W\$F= | 36.96T |
| CER= | 2.265 | COMVR=1.703 | DPLCC=.3391 | KLR= 3.026 | KLRM= | 1.513 |
| FFLBF= | .695 | FFLATP= .695 | FFL\$F=.4596 | | | |
| ----- | | | | | | |

Fig 4.9 Simulation Results - Attrition Formulation of Fighter Aircraft

| | | | | |
|---------------|--------------|---------------|---------------|--------------|
| TIME=12.00 | \$F=271.3 | AR\$FAT= 8.24 | EAT\$F=37.19A | ATP= 222. |
| ARAT\$F= 51.8 | E\$FAT=.1909 | MSATBF=.9534 | P\$F= 20.50T | W\$F= 36.96T |
| CER=2.265 | COMVR=1.703 | DPLCC=.3739 | KLR= 3.194 | KLRM= 1.597 |
| FFLBF= .795 | FFLATP= .795 | FFL\$F=.4976 | | |
| ----- | | | | |
| TIME=14.00 | \$F=258.5 | AR\$FAT= 4.49 | EAT\$F=37.19A | ATP= 121. |
| ARAT\$F= 49.3 | E\$FAT=.1909 | MSATBF=.9534 | P\$F= 20.50T | W\$F= 36.96T |
| CER=2.265 | COMVR=1.703 | DPLCC=.4131 | KLR= 3.408 | KLRM= 1.704 |
| FFLBF= .888 | FFLATP= .888 | FFL\$F=.5213 | | |
| ----- | | | | |
| TIME=16.00 | \$F=253.1 | AR\$FAT= .87 | EAT\$F=37.19A | ATP= 23. |
| ARAT\$F= 48.3 | E\$FAT=.1909 | MSATBF=.9534 | P\$F= 20.50T | W\$F= 36.96T |
| CER=2.265 | COMVR=1.703 | DPLCC=.4569 | KLR= 3.683 | KLRM= 1.841 |
| FFLBF= .978 | FFLATP= .978 | FFL\$F=.5314 | | |
| ----- | | | | |
| TIME=18.00 | \$F=252.8 | AR\$FAT= .00 | EAT\$F=37.19A | ATP= 0. |
| ARAT\$F= 48.3 | E\$FAT=.1909 | MSATBF=.9534 | P\$F= 20.50T | W\$F= 36.96T |
| CER=2.265 | COMVR=1.703 | DPLCC=.4682 | KLR= 3.761 | KLRM= 1.880 |
| FFLBF=1.000 | FFLATP=1.000 | FFL\$F=.5318 | | |
| ----- | | | | |
| TIME=20.00 | \$F=252.8 | AR\$FAT= .00 | EAT\$F=37.19A | ATP= 0. |
| ARAT\$F= 48.3 | E\$FAT=.1909 | MSATBF=.9534 | P\$F= 20.50T | W\$F= 36.96T |
| CER=2.265 | COMVR=1.703 | DPLCC=.4682 | KLR= 3.761 | KLRM= 1.880 |
| FFLBF=1.000 | FFLATP=1.000 | FFL\$F=.5318 | | |
| ----- | | | | |

Fig 4.9 (cont.)

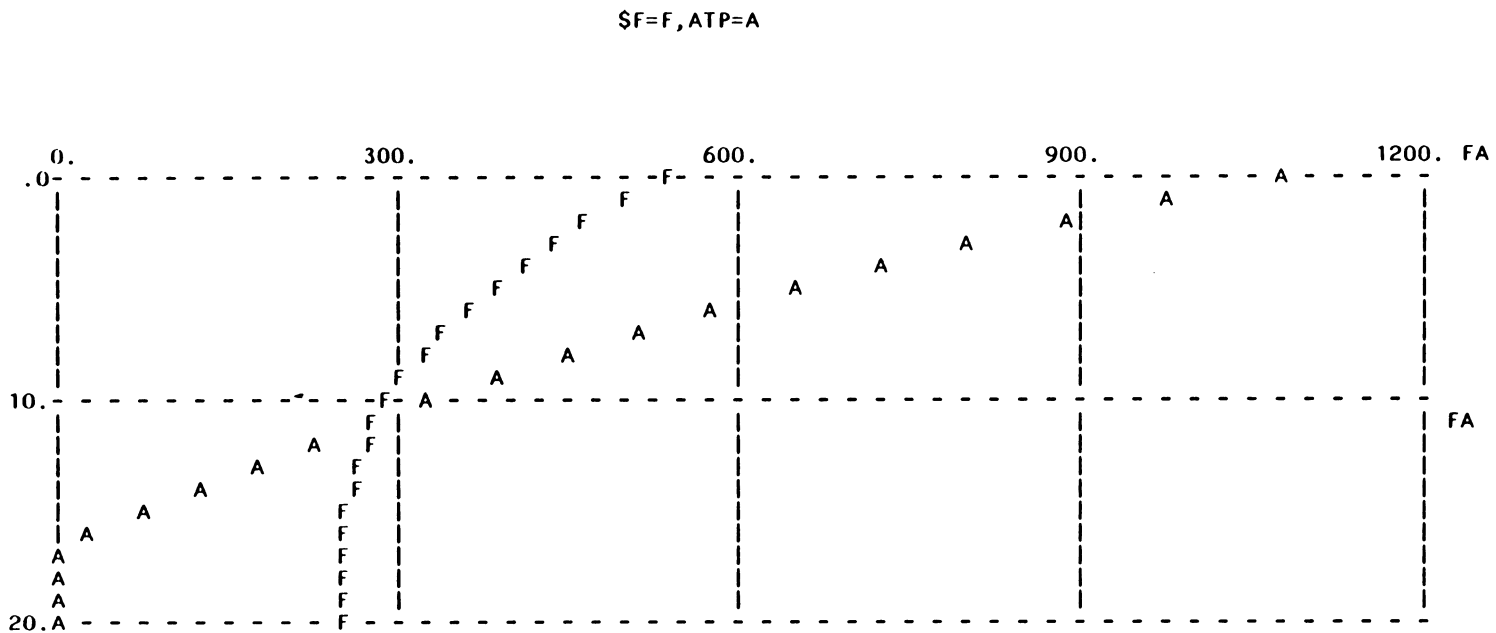


Fig 4.9 (cont.)

kill-loss ratio (KLR = 3.677 > 1). All these point to the fact that the modifications make the \$F\$ superior to the the ATP.

4.5 INCORPORATION OF DELTAS INTO TRADEOFF METHODOLOGY

Earlier in this chapter (in Section 4.4) the combat value ratio was defined and expressed in terms of attrition parameters as

$$\text{COMVR} = (M_0/B_0)\sqrt{c/b} \quad (4.36)$$

where $b = \text{SRB} * \text{AB} * (1 - \text{SM})$

and $c = \text{SRM} * \text{AM} * (1 - \text{SB})$

Now, the effective sortie rate for modified aircraft, SRM, can be expressed in terms of the sortie rate of the baseline aircraft, SRB as

$$\text{SRM} = \text{SRB} * \text{PM/PB} \quad (4.37)$$

Similarly, the availability of the modified aircraft can be expressed in terms of the availability of the baseline aircraft as

$$\text{AM} = \text{AB}/(1 - \text{DM}) \quad (4.38)$$

It is also clear that the relative inventories depend upon the delta acquisition cost and the relationship can be written as

$$M_0/B_0 = \text{AB}/\text{AM} = (1 - \text{DA})^{-1} \quad (4.39)$$

Substituting in equation 4.36 with the parameters obtained from equations 4.37 to 4.39 yields

$$\text{COMVR} = (1 - \text{DA})^{-1} \sqrt{\frac{(1 - \text{DPL})(1 - \text{SB})}{(1 - \text{DM})(1 - \text{SB} * (1 - \text{DS}))}} \quad (4.40)$$

where DPL is delta payload.

Baseline-Modified Aircraft Payload-Weight Relationship

The takeoff weight of an aircraft is the sum of its empty weight (W), fuel weight (F) and payload (P). Using a second letter to denote the aircraft we have WB, FB, and PB for the baseline aircraft and WM, FM, and PM for the modified aircraft.

The assumptions made in deriving the tradeoff input are:

1. the takeoff weights of the baseline and modified aircrafts are equal, and
2. the payload is carried only one way

from the first assumption we have

$$WB + FB + PB = WM + FM + PM \quad (4.41)$$

Since the fuel weight is proportional to the empty weight and payload carried, the second assumption can be expressed mathematically as

$$\frac{FB}{FM} = \frac{2WB+PB}{2WM+PM} \quad (4.42)$$

Solving equations 4.41 and 4.42 simultaneously for PM gives

$$PM = \frac{\left(\frac{WB+PB+FB-WM}{FB}\right) (2WB+PB) - 2WM}{1 + \left(\frac{2WB+PB}{FB}\right)} \quad (4.43)$$

Having dealt with the attrition formulations and the general tradeoff methodologies, models for applying the tradeoff analysis are presented next.

4.6 SURVIVABILITY TRADEOFF ANALYSIS FOR ATTACK AIRCRAFT

In this section the survivability tradeoff analysis is illustrated. The model used for the purpose of illustration is the one used in Section 4.3 (Figure 4.4). However in this case, reruns with the different deltas are utilized and the results are compared with those in Figure 4.6. The purpose of the tradeoff analysis is to determine if the modified aircraft (with the modifications indicated by the deltas) perform better than the baseline aircraft. In order to make a judgement on this issue the measures of effectiveness are utilized. The measures of effectiveness are the outputs of the tradeoff analysis whose inputs are the deltas obtained from the survivability assessment step.

In this section, besides the computer simulation, the analytical approach is used to develop a computational routine to assist decision making on the replacement of the baseline aircraft with modified ones. The measures of effectiveness are calculated in the computational routine on the basis of the discussions presented in Sections 4.2 and 4.3. A repetitive procedure is used in the computations, and based on it, relationships between the parameters and the measures of effectiveness are depicted graphically.

To compare baseline modified aircraft performance, each is attrited against a common surface threat. Then these results are compared with one another. Alternately, to compare the different modifications, reruns are made using the appropriate values of the parameters and the resulting measures of effectiveness compared. Figure 4.10 presents the results of reruns.

The computational routine to develop the curves for evaluation of the various alternatives is based on the analytical approach. The measures of effectiveness are computed in a stepwise manner and the main steps involved are illustrated in Table 4.2.

It is seen that ITDPL is a function of DSA and the payload. So it is possible to obtain a ITDPL as a function of DSA alone for specific values of the payload. Thus a family of curves can be obtained for various values of the payload, based on a series of computations as illustrated in Table 4.2.

A computer program, written in FORTRAN in this case, has been used to perform these computations. The program and the tabulation of the computations is presented in Figure 4.11. From these computations, the family of curves relating ITDPL and DSA for various payloads is obtained and the same is presented in Figure 4.12. The computations also show the cost elasticity of the targets destroyed per loss (CETDPL). CETDPL can also be incorporated into the Figure 4.12 with some adjustments to the figure. This is explained later in this chapter while describing the construction of the nomograph illustrating the survivability tradeoff analysis.

4.7 SURVIVABILITY TRADEOFF ANALYSIS FOR FIGHTER AIRCRAFT

In this section the survivability tradeoff analysis for fighter aircraft is illustrated. The model used for illustration has the modified fighter aircraft engaged in direct combat with the baseline aircraft to determine the superiority. In the attrition formulation model (Section

| | | | |
|----------|-------------------------|--------|------|
| | RUN RERUN BASELINE CASE | | |
| | DAA | DSA | DWA |
| PRESENT | 0. | 0. | 0. |
| ORIGINAL | -.93 | -17.5A | 81.A |

| | | | | |
|----------------|----------------|----------------|----------------|---------------|
| TIME= .0 | \$A=810.0 | AR\$ART= 64.80 | BA= 810.0 | ARBART= 64.80 |
| ITD\$AL=10.00E | PDT\$AL= .0 | PDTBAL= .0 | CPDT\$A= .0 | CPDTBA= .0 |
| CL\$A= .0 | CLBA= .0 | P\$ATDR=29.16M | PBATDR=29.16M | |
| ----- | | | | |
| TIME= 5.0 | \$A=538.5 | AR\$ART= 43.08 | BA= 538.5 | ARBART= 43.08 |
| ITD\$AL=10.00E | PDT\$AL=450.0T | PDTBAL=450.0T | CPDT\$A=122.2M | CPDTBA=122.2M |
| CL\$A= 271.5 | CLBA= 271.5 | P\$ATDR=19.39M | PBATDR=19.39M | |
| ----- | | | | |
| TIME= 10.0 | \$A=358.0 | AR\$ART= 28.64 | BA= 358.0 | ARBART= 28.64 |
| ITD\$AL=10.00E | PDT\$AL=450.0T | PDTBAL=450.0T | CPDT\$A=203.4M | CPDTBA=203.4M |
| CL\$A= 452.0 | CLBA= 452.0 | P\$ATDR=12.89M | PBATDR=12.89M | |
| ----- | | | | |
| TIME= 15.0 | \$A=238.0 | AR\$ART= 19.04 | BA= 238.0 | ARBART= 19.04 |
| ITD\$AL=10.00E | PDT\$AL=450.0T | PDTBAL=450.0T | CPDT\$A=257.4M | CPDTBA=257.4M |
| CL\$A= 572.0 | CLBA= 572.0 | P\$ATDR= 8.57M | PBATDR= 8.57M | |
| ----- | | | | |
| TIME= 20.0 | \$A=158.2 | AR\$ART= 12.66 | BA= 158.2 | ARBART= 12.66 |
| ITD\$AL=10.00E | PDT\$AL=450.0T | PDTBAL=450.0T | CPDT\$A=293.3M | CPDTBA=293.3M |
| CL\$A= 651.7 | CLBA= 651.7 | P\$ATDR= 5.70M | PBATDR= 5.70M | |
| ----- | | | | |
| TIME= 25.0 | \$A=105.2 | AR\$ART= 8.42 | BA= 105.2 | ARBART= 8.42 |
| ITD\$AL=10.00E | PDT\$AL=450.0T | PDTBAL=450.0T | CPDT\$A=317.2M | CPDTBA=317.2M |
| CL\$A= 704.8 | CLBA= 704.8 | P\$ATDR= 3.79M | PBATDR= 3.79M | |
| ----- | | | | |
| TIME= 30.0 | \$A= 69.9 | AR\$ART= 5.60 | BA= 69.9 | ARBART= 5.60 |
| ITD\$AL=10.00E | PDT\$AL=450.0T | PDTBAL=450.0T | CPDT\$A=333.0M | CPDTBA=333.0M |
| CL\$A= 740.0 | CLBA= 740.0 | P\$ATDR= 2.52M | PBATDR= 2.52M | |
| ----- | | | | |
| TIME= 35.0 | \$A= 46.5 | AR\$ART= 3.72 | BA= 46.5 | ARBART= 3.72 |
| ITD\$AL=10.00E | PDT\$AL=450.0T | PDTBAL=450.0T | CPDT\$A=343.6M | CPDTBA=343.6M |
| CL\$A= 763.5 | CLBA= 763.5 | P\$ATDR= 1.67M | PBATDR= 1.67M | |
| ----- | | | | |
| TIME= 40.0 | \$A= 30.9 | AR\$ART= 2.47 | BA= 30.9 | ARBART= 2.47 |
| ITD\$AL=10.00E | PDT\$AL=450.0T | PDTBAL=450.0T | CPDT\$A=350.6M | CPDTBA=350.6M |
| CL\$A= 779.1 | CLBA= 779.1 | P\$ATDR= 1.11M | PBATDR= 1.11M | |
| ----- | | | | |
| TIME= 45.0 | \$A= 20.6 | AR\$ART= 1.64 | BA= 20.6 | ARBART= 1.64 |
| ITD\$AL=10.00E | PDT\$AL=450.0T | PDTBAL=450.0T | CPDT\$A=355.2M | CPDTBA=355.2M |
| CL\$A= 789.4 | CLBA= 789.4 | P\$ATDR= .74M | PBATDR= .74M | |
| ----- | | | | |
| TIME= 50.0 | \$A= 13.7 | AR\$ART= 1.09 | BA= 13.7 | ARBART= 1.09 |
| ITD\$AL=10.00E | PDT\$AL=450.0T | PDTBAL=450.0T | CPDT\$A=358.3M | CPDTBA=358.3M |
| CL\$A= 796.3 | CLBA= 796.3 | P\$ATDR= .49M | PBATDR= .49M | |
| ----- | | | | |

Fig 4.10 Simulation Results - Tradeoff Analysis for Attack Aircraft

| | | | | |
|---------------|----------------|---------------|----------------|---------------|
| TIME= 55.0 | SA= 9.1 | ARSAART= .73 | BA= 9.1 | ARBART= .73 |
| ITDSAL=10.00E | PDT\$AL=450.0T | PDTBAL=450.0T | CPDT\$A=360.4M | CPDTBA=360.4M |
| CLSA= 800.9 | CLBA= 800.9 | P\$ATDR= .33M | PBATDR= .33M | |
| ----- | | | | |
| TIME= 60.0 | SA= 6.0 | ARSAART= .48 | BA= 6.0 | ARBART= .48 |
| ITDSAL=10.00E | PDT\$AL=450.0T | PDTBAL=450.0T | CPDT\$A=361.8M | CPDTBA=361.8M |
| CLSA= 803.9 | CLBA= 803.9 | P\$ATDR= .22M | PBATDR= .22M | |
| ----- | | | | |
| TIME= 65.0 | SA= 4.0 | ARSAART= .32 | BA= 4.0 | ARBART= .32 |
| ITDSAL=10.00E | PDT\$AL=450.0T | PDTBAL=450.0T | CPDT\$A=362.7M | CPDTBA=362.7M |
| CLSA= 806.0 | CLBA= 806.0 | P\$ATDR= .14M | PBATDR= .14M | |
| ----- | | | | |
| TIME= 70.0 | SA= 2.7 | ARSAART= .21 | BA= 2.7 | ARBART= .21 |
| ITDSAL=10.00E | PDT\$AL=450.0T | PDTBAL=450.0T | CPDT\$A=363.3M | CPDTBA=363.3M |
| CLSA= 807.3 | CLBA= 807.3 | P\$ATDR= .10M | PBATDR= .10M | |
| ----- | | | | |
| TIME= 75.0 | SA= 1.8 | ARSAART= .14 | BA= 1.8 | ARBART= .14 |
| ITDSAL=10.00E | PDT\$AL=450.0T | PDTBAL=450.0T | CPDT\$A=363.7M | CPDTBA=363.7M |
| CLSA= 808.2 | CLBA= 808.2 | P\$ATDR= .06M | PBATDR= .06M | |
| ----- | | | | |
| TIME= 80.0 | SA= 1.2 | ARSAART= .09 | BA= 1.2 | ARBART= .09 |
| ITDSAL=10.00E | PDT\$AL=450.0T | PDTBAL=450.0T | CPDT\$A=364.0M | CPDTBA=364.0M |
| CLSA= 808.8 | CLBA= 808.8 | P\$ATDR= .04M | PBATDR= .04M | |
| ----- | | | | |
| TIME= 85.0 | SA= .8 | ARSAART= .06 | BA= .8 | ARBART= .06 |
| ITDSAL=10.00E | PDT\$AL=450.0T | PDTBAL=450.0T | CPDT\$A=364.1M | CPDTBA=364.1M |
| CLSA= 809.2 | CLBA= 809.2 | P\$ATDR= .03M | PBATDR= .03M | |
| ----- | | | | |
| TIME= 90.0 | SA= .5 | ARSAART= .04 | BA= .5 | ARBART= .04 |
| ITDSAL=10.00E | PDT\$AL=450.0T | PDTBAL=450.0T | CPDT\$A=364.2M | CPDTBA=364.2M |
| CLSA= 809.5 | CLBA= 809.5 | P\$ATDR= .02M | PBATDR= .02M | |
| ----- | | | | |
| TIME= 95.0 | SA= .3 | ARSAART= .03 | BA= .3 | ARBART= .03 |
| ITDSAL=10.00E | PDT\$AL=450.0T | PDTBAL=450.0T | CPDT\$A=364.3M | CPDTBA=364.3M |
| CLSA= 809.6 | CLBA= 809.6 | P\$ATDR= .01M | PBATDR= .01M | |
| ----- | | | | |
| TIME=100.0 | SA= .2 | ARSAART= .02 | BA= .2 | ARBART= .02 |
| ITDSAL=10.00E | PDT\$AL=450.0T | PDTBAL=450.0T | CPDT\$A=364.4M | CPDTBA=364.4M |
| CLSA= 809.7 | CLBA= 809.7 | P\$ATDR= .01M | PBATDR= .01M | |
| ----- | | | | |

Fig 4.10 (cont.)

| | | |
|----------|------|--------|
| | DAA | DSA |
| PRESENT | -.8 | -15.A |
| ORIGINAL | -.93 | -17.5A |

| | | | | |
|---------------|----------------|----------------|----------------|---------------|
| TIME= .0 | SA=810.0 | AR\$ART= 41.47 | BA= 1458. | ARBART= 116.6 |
| ITDSAL= .0000 | PDT\$AL= .0 | PDTBAL= .0 | CPDT\$A= .0 | CPDTBA= .0 |
| CL\$A= .0 | CLBA= .0 | P\$ATDR=33.21M | PBATDR=52.49M | CETDPL= .0000 |
| ----- | | | | |
| TIME= 5.0 | SA=625.0 | AR\$ART= 32.00 | BA= 969. | ARBART= 77.5 |
| ITDSAL= .7793 | PDT\$AL=800.7T | PDTBAL=450.0T | CPDT\$A=148.2M | CPDTBA=219.9M |
| CL\$A= 185.0 | CLBA=489. | P\$ATDR=25.62M | PBATDR=34.90M | CETDPL= .9741 |
| ----- | | | | |
| TIME= 10.0 | SA=482.2 | AR\$ART= 24.69 | BA= 644. | ARBART= 51.6 |
| ITDSAL= .7793 | PDT\$AL=800.7T | PDTBAL=450.0T | CPDT\$A=262.5M | CPDTBA=366.1M |
| CL\$A= 327.8 | CLBA=814. | P\$ATDR=19.77M | PBATDR=23.20M | CETDPL= .9741 |
| ----- | | | | |
| TIME= 15.0 | SA=372.0 | AR\$ART= 19.05 | BA= 428. | ARBART= 34.3 |
| ITDSAL= .7793 | PDT\$AL=800.7T | PDTBAL=450.0T | CPDT\$A=350.7M | CPDTBA=463.3M |
| CL\$A= 438.0 | CLBA= 1030. | P\$ATDR=15.25M | PBATDR=15.42M | CETDPL= .9741 |
| ----- | | | | |
| TIME= 20.0 | SA=287.1 | AR\$ART= 14.70 | BA= 285. | ARBART= 22.8 |
| ITDSAL= .7793 | PDT\$AL=800.7T | PDTBAL=450.0T | CPDT\$A=418.7M | CPDTBA=527.9M |
| CL\$A= 522.9 | CLBA= 1173. | P\$ATDR=11.77M | PBATDR=10.25M | CETDPL= .9741 |
| ----- | | | | |
| TIME= 25.0 | SA=221.5 | AR\$ART= 11.34 | BA= 189. | ARBART= 15.1 |
| ITDSAL= .7793 | PDT\$AL=800.7T | PDTBAL=450.0T | CPDT\$A=471.2M | CPDTBA=570.9M |
| CL\$A= 588.5 | CLBA= 1269. | P\$ATDR= 9.08M | PBATDR= 6.82M | CETDPL= .9741 |
| ----- | | | | |
| TIME= 30.0 | SA=170.9 | AR\$ART= 8.75 | BA= 126. | ARBART= 10.1 |
| ITDSAL= .7793 | PDT\$AL=800.7T | PDTBAL=450.0T | CPDT\$A=511.7M | CPDTBA=599.4M |
| CL\$A= 639.1 | CLBA= 1332. | P\$ATDR= 7.01M | PBATDR= 4.53M | CETDPL= .9741 |
| ----- | | | | |
| TIME= 35.0 | SA=131.8 | AR\$ART= 6.75 | BA= 84. | ARBART= 6.7 |
| ITDSAL= .7793 | PDT\$AL=800.7T | PDTBAL=450.0T | CPDT\$A=543.0M | CPDTBA=618.4M |
| CL\$A= 678.1 | CLBA= 1374. | P\$ATDR= 5.41M | PBATDR= 3.01M | CETDPL= .9741 |
| ----- | | | | |
| TIME= 40.0 | SA=101.7 | AR\$ART= 5.21 | BA= 56. | ARBART= 4.5 |
| ITDSAL= .7793 | PDT\$AL=800.7T | PDTBAL=450.0T | CPDT\$A=567.1M | CPDTBA=631.0M |
| CL\$A= 708.3 | CLBA= 1402. | P\$ATDR= 4.17M | PBATDR= 2.00M | CETDPL= .9741 |
| ----- | | | | |
| TIME= 45.0 | SA= 78.5 | AR\$ART= 4.02 | BA= 37. | ARBART= 3.0 |
| ITDSAL= .7793 | PDT\$AL=800.7T | PDTBAL=450.0T | CPDT\$A=585.7M | CPDTBA=639.4M |
| CL\$A= 731.5 | CLBA= 1421. | P\$ATDR= 3.22M | PBATDR= 1.33M | CETDPL= .9741 |
| ----- | | | | |
| TIME= 50.0 | SA= 60.6 | AR\$ART= 3.10 | BA= 25. | ARBART= 2.0 |
| ITDSAL= .7793 | PDT\$AL=800.7T | PDTBAL=450.0T | CPDT\$A=600.0M | CPDTBA=645.0M |
| CL\$A= 749.4 | CLBA= 1433. | P\$ATDR= 2.48M | PBATDR= .89M | CETDPL= .9741 |
| ----- | | | | |

Fig 4.10 (cont.) ALTERNATIVE SURVIVABILITY ENHANCEMENT

| | | | | |
|----------------|----------------|----------------|----------------|---------------|
| TIME= 55.0 | SA= 46.7 | AR\$ART= 2.39 | BA= 16. | ARBART= 1.3 |
| ITD\$AL= .7793 | PDT\$AL=800.7T | PDTBAL=450.0T | CPDT\$A=611.1M | CPDTBA=648.7M |
| CL\$A= 763.3 | CLBA= 1442. | P\$ATDR= 1.92M | PBATDR= .59M | CETDPL= .9741 |
| TIME= 60.0 | SA= 36.1 | AR\$ART= 1.85 | BA= 11. | ARBART= .9 |
| ITD\$AL= .7793 | PDT\$AL=800.7T | PDTBAL=450.0T | CPDT\$A=619.7M | CPDTBA=651.2M |
| CL\$A= 773.9 | CLBA= 1447. | P\$ATDR= 1.48M | PBATDR= .39M | CETDPL= .9741 |
| TIME= 65.0 | SA= 27.8 | AR\$ART= 1.42 | BA= 7. | ARBART= .6 |
| ITD\$AL= .7793 | PDT\$AL=800.7T | PDTBAL=450.0T | CPDT\$A=626.3M | CPDTBA=652.8M |
| CL\$A= 782.2 | CLBA= 1451. | P\$ATDR= 1.14M | PBATDR= .26M | CETDPL= .9741 |
| TIME= 70.0 | SA= 21.5 | AR\$ART= 1.10 | BA= 5. | ARBART= .4 |
| ITD\$AL= .7793 | PDT\$AL=800.7T | PDTBAL=450.0T | CPDT\$A=631.3M | CPDTBA=653.9M |
| CL\$A= 788.5 | CLBA= 1453. | P\$ATDR= .88M | PBATDR= .17M | CETDPL= .9741 |
| TIME= 75.0 | SA= 16.6 | AR\$ART= .85 | BA= 3. | ARBART= .3 |
| ITD\$AL= .7793 | PDT\$AL=800.7T | PDTBAL=450.0T | CPDT\$A=635.3M | CPDTBA=654.6M |
| CL\$A= 793.4 | CLBA= 1455. | P\$ATDR= .68M | PBATDR= .12M | CETDPL= .9741 |
| TIME= 80.0 | SA= 12.8 | AR\$ART= .65 | BA= 2. | ARBART= .2 |
| ITD\$AL= .7793 | PDT\$AL=800.7T | PDTBAL=450.0T | CPDT\$A=638.3M | CPDTBA=655.1M |
| CL\$A= 797.2 | CLBA= 1456. | P\$ATDR= .52M | PBATDR= .08M | CETDPL= .9741 |
| TIME= 85.0 | SA= 9.9 | AR\$ART= .50 | BA= 1. | ARBART= .1 |
| ITD\$AL= .7793 | PDT\$AL=800.7T | PDTBAL=450.0T | CPDT\$A=640.6M | CPDTBA=655.4M |
| CL\$A= 800.1 | CLBA= 1457. | P\$ATDR= .40M | PBATDR= .05M | CETDPL= .9741 |
| TIME= 90.0 | SA= 7.6 | AR\$ART= .39 | BA= 1. | ARBART= .1 |
| ITD\$AL= .7793 | PDT\$AL=800.7T | PDTBAL=450.0T | CPDT\$A=642.4M | CPDTBA=655.6M |
| CL\$A= 802.4 | CLBA= 1457. | P\$ATDR= .31M | PBATDR= .03M | CETDPL= .9741 |
| TIME= 95.0 | SA= 5.9 | AR\$ART= .30 | BA= 1. | ARBART= .0 |
| ITD\$AL= .7793 | PDT\$AL=800.7T | PDTBAL=450.0T | CPDT\$A=643.8M | CPDTBA=655.8M |
| CL\$A= 804.1 | CLBA= 1457. | P\$ATDR= .24M | PBATDR= .02M | CETDPL= .9741 |
| TIME=100.0 | SA= 4.5 | AR\$ART= .23 | BA= 0. | ARBART= .0 |
| ITD\$AL= .7793 | PDT\$AL=800.7T | PDTBAL=450.0T | CPDT\$A=644.9M | CPDTBA=655.9M |
| CL\$A= 805.4 | CLBA= 1458. | P\$ATDR= .19M | PBATDR= .01M | CETDPL= .9741 |

Fig 4.10 (cont.)

| | | |
|----------|------|--------|
| | DAA | DSA |
| PRESENT | -.8 | -15.A |
| ORIGINAL | -.93 | -17.5A |

| | | | | | | | | | |
|----------|-------|----------|----------|----------|--------|----------|---------|---------|--------|
| TIME= | .0 | SA=810.0 | AR\$ART= | 41.47 | BA= | 1458. | ARBART= | 116.6 | |
| ITD\$AL= | .0000 | PDT\$AL= | .0 | PDTBAL= | .0 | CPDT\$A= | .0 | CPDTBA= | .0 |
| CL\$A= | .0 | CLBA= | 0. | P\$ATDR= | 33.21M | PBATDR= | 52.49M | CETDPL= | .0000 |
| ----- | | | | | | | | | |
| TIME= | 5.0 | SA=625.0 | AR\$ART= | 32.00 | BA= | 969. | ARBART= | 77.5 | |
| ITD\$AL= | .7793 | PDT\$AL= | 800.7T | PDTBAL= | 450.0T | CPDT\$A= | 148.2M | CPDTBA= | 219.9M |
| CL\$A= | 185.0 | CLBA= | 489. | P\$ATDR= | 25.62M | PBATDR= | 34.90M | CETDPL= | .9741 |
| ----- | | | | | | | | | |
| TIME= | 10.0 | SA=482.2 | AR\$ART= | 24.69 | BA= | 644. | ARBART= | 51.6 | |
| ITD\$AL= | .7793 | PDT\$AL= | 800.7T | PDTBAL= | 450.0T | CPDT\$A= | 262.5M | CPDTBA= | 366.1M |
| CL\$A= | 327.8 | CLBA= | 814. | P\$ATDR= | 19.77M | PBATDR= | 23.20M | CETDPL= | .9741 |
| ----- | | | | | | | | | |
| TIME= | 15.0 | SA=372.0 | AR\$ART= | 19.05 | BA= | 428. | ARBART= | 34.3 | |
| ITD\$AL= | .7793 | PDT\$AL= | 800.7T | PDTBAL= | 450.0T | CPDT\$A= | 350.7M | CPDTBA= | 463.3M |
| CL\$A= | 438.0 | CLBA= | 1030. | P\$ATDR= | 15.25M | PBATDR= | 15.42M | CETDPL= | .9741 |
| ----- | | | | | | | | | |
| TIME= | 20.0 | SA=287.1 | AR\$ART= | 14.70 | BA= | 285. | ARBART= | 22.8 | |
| ITD\$AL= | .7793 | PDT\$AL= | 800.7T | PDTBAL= | 450.0T | CPDT\$A= | 418.7M | CPDTBA= | 527.9M |
| CL\$A= | 522.9 | CLBA= | 1173. | P\$ATDR= | 11.77M | PBATDR= | 10.25M | CETDPL= | .9741 |
| ----- | | | | | | | | | |
| TIME= | 25.0 | SA=221.5 | AR\$ART= | 11.34 | BA= | 189. | ARBART= | 15.1 | |
| ITD\$AL= | .7793 | PDT\$AL= | 800.7T | PDTBAL= | 450.0T | CPDT\$A= | 471.2M | CPDTBA= | 570.9M |
| CL\$A= | 588.5 | CLBA= | 1269. | P\$ATDR= | 9.08M | PBATDR= | 6.82M | CETDPL= | .9741 |
| ----- | | | | | | | | | |
| TIME= | 30.0 | SA=170.9 | AR\$ART= | 8.75 | BA= | 126. | ARBART= | 10.1 | |
| ITD\$AL= | .7793 | PDT\$AL= | 800.7T | PDTBAL= | 450.0T | CPDT\$A= | 511.7M | CPDTBA= | 599.4M |
| CL\$A= | 639.1 | CLBA= | 1332. | P\$ATDR= | 7.01M | PBATDR= | 4.53M | CETDPL= | .9741 |
| ----- | | | | | | | | | |
| TIME= | 35.0 | SA=131.8 | AR\$ART= | 6.75 | BA= | 84. | ARBART= | 6.7 | |
| ITD\$AL= | .7793 | PDT\$AL= | 800.7T | PDTBAL= | 450.0T | CPDT\$A= | 543.0M | CPDTBA= | 618.4M |
| CL\$A= | 678.1 | CLBA= | 1374. | P\$ATDR= | 5.41M | PBATDR= | 3.01M | CETDPL= | .9741 |
| ----- | | | | | | | | | |
| TIME= | 40.0 | SA=101.7 | AR\$ART= | 5.21 | BA= | 56. | ARBART= | 4.5 | |
| ITD\$AL= | .7793 | PDT\$AL= | 800.7T | PDTBAL= | 450.0T | CPDT\$A= | 567.1M | CPDTBA= | 631.0M |
| CL\$A= | 708.3 | CLBA= | 1402. | P\$ATDR= | 4.17M | PBATDR= | 2.00M | CETDPL= | .9741 |
| ----- | | | | | | | | | |
| TIME= | 45.0 | SA= 78.5 | AR\$ART= | 4.02 | BA= | 37. | ARBART= | 3.0 | |
| ITD\$AL= | .7793 | PDT\$AL= | 800.7T | PDTBAL= | 450.0T | CPDT\$A= | 585.7M | CPDTBA= | 639.4M |
| CL\$A= | 731.5 | CLBA= | 1421. | P\$ATDR= | 3.22M | PBATDR= | 1.33M | CETDPL= | .9741 |
| ----- | | | | | | | | | |
| TIME= | 50.0 | SA= 60.6 | AR\$ART= | 3.10 | BA= | 25. | ARBART= | 2.0 | |
| ITD\$AL= | .7793 | PDT\$AL= | 800.7T | PDTBAL= | 450.0T | CPDT\$A= | 600.0M | CPDTBA= | 645.0M |
| CL\$A= | 749.4 | CLBA= | 1433. | P\$ATDR= | 2.48M | PBATDR= | .89M | CETDPL= | .9741 |
| ----- | | | | | | | | | |

Fig 4.10 (cont.) ALTERNATIVE SURVIVABILITY ENHANCEMENT : 2

| | | | | |
|----------------|----------------|----------------|----------------|---------------|
| TIME= 55.0 | SA= 46.7 | AR\$ART= 2.39 | BA= 16. | ARBART= 1.3 |
| ITD\$AL= .7793 | PDT\$AL=800.7T | PDTBAL=450.0T | CPDT\$A=611.1M | CPDTBA=648.7M |
| CL\$A= 763.3 | CLBA= 1442. | P\$ATDR= 1.92M | PBATDR= .59M | CETDPL= .9741 |
| TIME= 60.0 | SA= 36.1 | AR\$ART= 1.85 | BA= 11. | ARBART= .9 |
| ITD\$AL= .7793 | PDT\$AL=800.7T | PDTBAL=450.0T | CPDT\$A=619.7M | CPDTBA=651.2M |
| CL\$A= 773.9 | CLBA= 1447. | P\$ATDR= 1.48M | PBATDR= .39M | CETDPL= .9741 |
| TIME= 65.0 | SA= 27.8 | AR\$ART= 1.42 | BA= 7. | ARBART= .6 |
| ITD\$AL= .7793 | PDT\$AL=800.7T | PDTBAL=450.0T | CPDT\$A=626.3M | CPDTBA=652.8M |
| CL\$A= 782.2 | CLBA= 1451. | P\$ATDR= 1.14M | PBATDR= .26M | CETDPL= .9741 |
| TIME= 70.0 | SA= 21.5 | AR\$ART= 1.10 | BA= 5. | ARBART= .4 |
| ITD\$AL= .7793 | PDT\$AL=800.7T | PDTBAL=450.0T | CPDT\$A=631.3M | CPDTBA=653.9M |
| CL\$A= 788.5 | CLBA= 1453. | P\$ATDR= .88M | PBATDR= .17M | CETDPL= .9741 |
| TIME= 75.0 | SA= 16.6 | AR\$ART= .85 | BA= 3. | ARBART= .3 |
| ITD\$AL= .7793 | PDT\$AL=800.7T | PDTBAL=450.0T | CPDT\$A=635.3M | CPDTBA=654.6M |
| CL\$A= 793.4 | CLBA= 1455. | P\$ATDR= .68M | PBATDR= .12M | CETDPL= .9741 |
| TIME= 80.0 | SA= 12.8 | AR\$ART= .65 | BA= 2. | ARBART= .2 |
| ITD\$AL= .7793 | PDT\$AL=800.7T | PDTBAL=450.0T | CPDT\$A=638.3M | CPDTBA=655.1M |
| CL\$A= 797.2 | CLBA= 1456. | P\$ATDR= .52M | PBATDR= .08M | CETDPL= .9741 |
| TIME= 85.0 | SA= 9.9 | AR\$ART= .50 | BA= 1. | ARBART= .1 |
| ITD\$AL= .7793 | PDT\$AL=800.7T | PDTBAL=450.0T | CPDT\$A=640.6M | CPDTBA=655.4M |
| CL\$A= 800.1 | CLBA= 1457. | P\$ATDR= .40M | PBATDR= .05M | CETDPL= .9741 |
| TIME= 90.0 | SA= 7.6 | AR\$ART= .39 | BA= 1. | ARBART= .1 |
| ITD\$AL= .7793 | PDT\$AL=800.7T | PDTBAL=450.0T | CPDT\$A=642.4M | CPDTBA=655.6M |
| CL\$A= 802.4 | CLBA= 1457. | P\$ATDR= .31M | PBATDR= .03M | CETDPL= .9741 |
| TIME= 95.0 | SA= 5.9 | AR\$ART= .30 | BA= 1. | ARBART= .0 |
| ITD\$AL= .7793 | PDT\$AL=800.7T | PDTBAL=450.0T | CPDT\$A=643.8M | CPDTBA=655.8M |
| CL\$A= 804.1 | CLBA= 1457. | P\$ATDR= .24M | PBATDR= .02M | CETDPL= .9741 |
| TIME=100.0 | SA= 4.5 | AR\$ART= .23 | BA= 0. | ARBART= .0 |
| ITD\$AL= .7793 | PDT\$AL=800.7T | PDTBAL=450.0T | CPDT\$A=644.9M | CPDTBA=655.9M |
| CL\$A= 805.4 | CLBA= 1458. | P\$ATDR= .19M | PBATDR= .01M | CETDPL= .9741 |

Fig 4.10 (cont.)

Table 4.2 Steps in the Computational Routine for Attack Aircraft

| Parameter | Symbol | How Obtained |
|---|--------|--------------------------|
| 1. Delta Acquisition Cost | DAA | input |
| 2. Survivability of Baseline Aircraft | SBA | input |
| 3. Delta Survivability | DSA | input |
| 4. Survivability of Modified Aircraft | SMA | $SBA(1-DSA)$ |
| 5. Payload of Baseline Aircraft | PBA | input |
| 6. Payload of Modified Aircraft * | PMA | input |
| 7. Payload Delivered to Target per Baseline Aircraft Cost | PDTPBL | $PBA/(1-SBA)$ |
| 8. Payload Delivered to Target per Modified Aircraft Cost | PDTPML | $PMA/(1-SMA)$ |
| 9. Increased Targets Destroyed per Loss | ITDPL | $(PDTPML-PDTPBL)/PDTPBL$ |
| 10. Increase in Cost per Aircraft | ICPA | -DAA |
| 11. Cost Elasticity of Target Destroyed Per Loss | CETDPL | $ITDPL/ICPA$ |

* PMA can also be calculated using Delta Weight (DW) as per equation 4.43 wherein DW is to be given as an input.

***** Replacement of A-6 Attack Aircraft With Modified Aircraft *****

```

REAL ITDPL,ICPA
DIMENSION SBA(6), DSA(6), SMA(6), PBA(6), PMA(6), PDTPBL(6),
1 PDTPML(6), ITDPL(6),ICPA(6),CETDPL(6),DAA(6)
READ (5,*) NDSA
READ (5,*) (DSA(IDSA),IDSA=1,NDSA)
READ (5,*) (DAA(ID),ID=1,6)
DO 9 NPMA = 1,8
DO 19 IN =1,NDSA
SBA(IN) = .96
PBA(IN) = 18.000
PMA(IN) = PBA(IN) + NPMA -1.0
IF(NPMA.EQ.4) PMA(IN) = PBA(IN) + NPMA -1.5
IF(NPMA.GT.4) PMA(IN) = PBA(IN) + NPMA -2.0
ICPA(IN) = -DAA(IN)
SMA(IN) = SBA(IN) * (1-DSA(IN))
PDTPBL(IN) = PBA(IN) / ( 1 - SBA(IN) )
PDTPML(IN) = PMA(IN) / ( 1 - SMA(IN) )
ITDPL(IN) = (PDTPML(IN) - PDTPBL(IN)) / PDTPBL(IN)
CETDPL(IN) = ITDPL(IN) / ICPA(IN)
19 CONTINUE
WRITE(6,200) (DAA(IN),IN=1,NDSA)
WRITE(6,210) (SBA(IN),IN=1,NDSA)
WRITE(6,220) (DSA(IN),IN=1,NDSA)
WRITE(6,230) (SMA(IN),IN=1,NDSA)
WRITE(6,240) (PBA(IN),IN=1,NDSA)
WRITE(6,250) (PMA(IN),IN=1,NDSA)
WRITE(6,260) (PDTPBL(IN),IN=1,NDSA)
WRITE(6,270) (PDTPML(IN),IN=1,NDSA)
WRITE(6,280) (ITDPL(IN),IN=1,NDSA)
WRITE(6,290) (ICPA(IN),IN=1,NDSA)
WRITE(6,300) (CETDPL(IN),IN=1,NDSA)
200 FORMAT(/5X,'DAA',5X,6(F8.4,2X) )
210 FORMAT(5X,'SBA',5X,6(F8.4,2X) )
220 FORMAT(5X,'DSA',5X,6(F8.4,2X) )
230 FORMAT(5X,'SMA',5X,6(F8.4,2X) )
240 FORMAT(5X,'PBA',5X,6(F8.4,2X) )
250 FORMAT(5X,'PMA',5X,6(F8.4,2X) )
260 FORMAT(5X,'PDTPBL',2X,6(F8.2,2X) )
270 FORMAT(5X,'PDTPML',2X,6(F8.2,2X) )
280 FORMAT(5X,'ITDPL',3X,6(F8.4,2X) )
290 FORMAT(5X,'ICPA',4X,6(F8.4,2X) )
300 FORMAT(5X,'CETDPL',2X,6(F8.4,2X)/3X,70(' -' ) )
9 CONTINUE
STOP
END

```

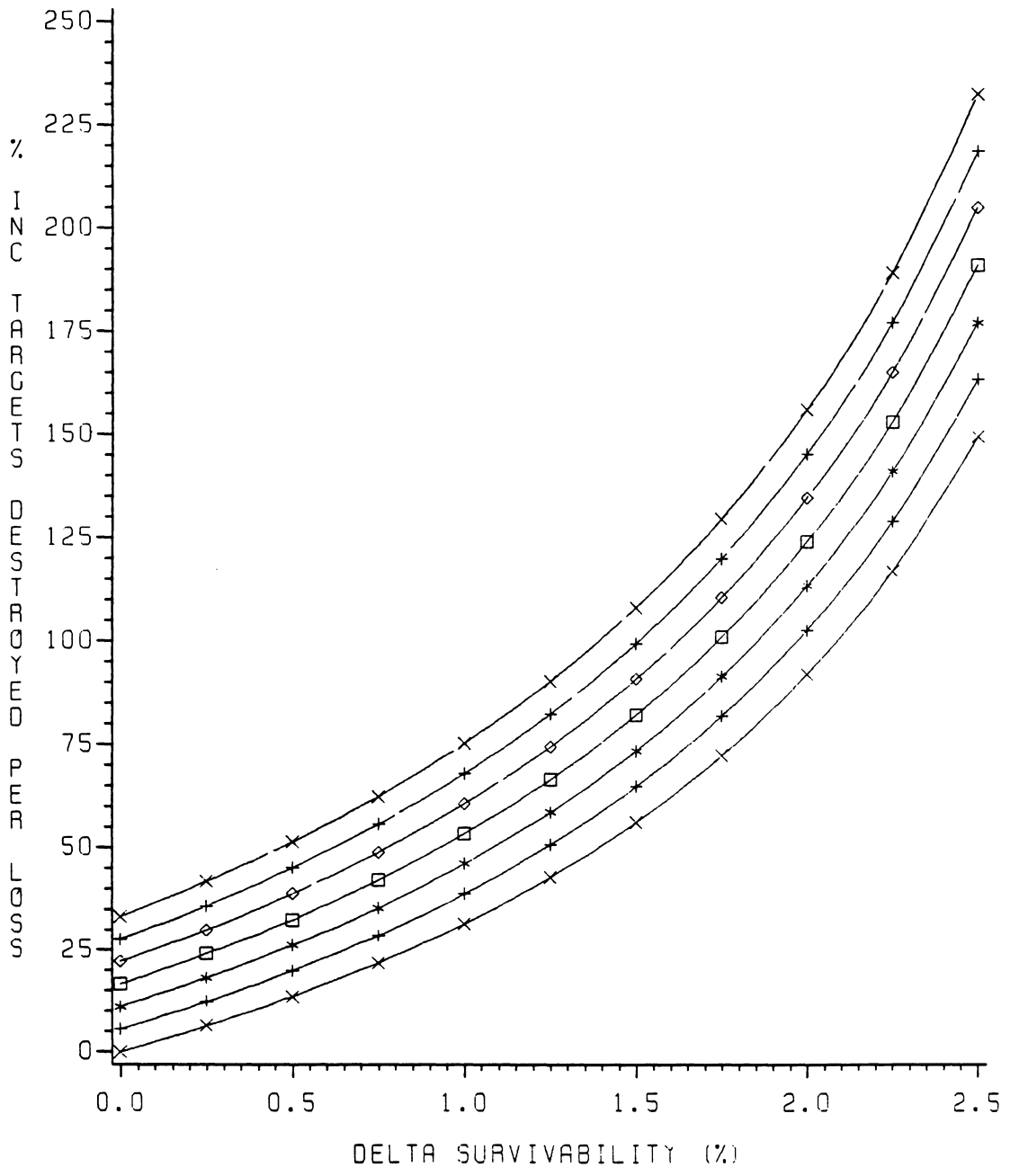
Fig 4.11 Computational Routine for Attack Aircraft

| | | | | | | |
|--------|---------|---------|---------|---------|---------|---------|
| DAA | -0.9300 | -0.9300 | -0.9300 | -0.9300 | -0.9300 | -0.9300 |
| SBA | 0.9600 | 0.9600 | 0.9600 | 0.9600 | 0.9600 | 0.9600 |
| DSA | 0.0000 | -0.0100 | -0.0175 | -0.0200 | -0.0250 | -0.0300 |
| SMA | 0.9600 | 0.9696 | 0.9768 | 0.9792 | 0.9840 | 0.9888 |
| PBA | 18.0000 | 18.0000 | 18.0000 | 18.0000 | 18.0000 | 18.0000 |
| PMA | 18.0000 | 18.0000 | 18.0000 | 18.0000 | 18.0000 | 18.0000 |
| PDTPBL | 450.00 | 450.00 | 450.00 | 450.00 | 450.00 | 450.00 |
| PDTPML | 450.00 | 592.09 | 775.86 | 865.36 | 1124.97 | 1607.10 |
| ITDPL | 0.0000 | 0.3158 | 0.7241 | 0.9230 | 1.4999 | 2.5713 |
| ICPA | 0.9300 | 0.9300 | 0.9300 | 0.9300 | 0.9300 | 0.9300 |
| CETDPL | 0.0000 | 0.3395 | 0.7786 | 0.9925 | 1.6128 | 2.7649 |
| ----- | | | | | | |
| DAA | -0.9300 | -0.9300 | -0.9300 | -0.9300 | -0.9300 | -0.9300 |
| SBA | 0.9600 | 0.9600 | 0.9600 | 0.9600 | 0.9600 | 0.9600 |
| DSA | 0.0000 | -0.0100 | -0.0175 | -0.0200 | -0.0250 | -0.0300 |
| SMA | 0.9600 | 0.9696 | 0.9768 | 0.9792 | 0.9840 | 0.9888 |
| PBA | 18.0000 | 18.0000 | 18.0000 | 18.0000 | 18.0000 | 18.0000 |
| PMA | 19.0000 | 19.0000 | 19.0000 | 19.0000 | 19.0000 | 19.0000 |
| PDTPBL | 450.00 | 450.00 | 450.00 | 450.00 | 450.00 | 450.00 |
| PDTPML | 475.00 | 624.98 | 818.96 | 913.44 | 1187.47 | 1696.38 |
| ITDPL | 0.0556 | 0.3889 | 0.8199 | 1.0299 | 1.6388 | 2.7697 |
| ICPA | 0.9300 | 0.9300 | 0.9300 | 0.9300 | 0.9300 | 0.9300 |
| CETDPL | 0.0597 | 0.4181 | 0.8816 | 1.1074 | 1.7622 | 2.9782 |
| ----- | | | | | | |
| DAA | -0.9300 | -0.9300 | -0.9300 | -0.9300 | -0.9300 | -0.9300 |
| SBA | 0.9600 | 0.9600 | 0.9600 | 0.9600 | 0.9600 | 0.9600 |
| DSA | 0.0000 | -0.0100 | -0.0175 | -0.0200 | -0.0250 | -0.0300 |
| SMA | 0.9600 | 0.9696 | 0.9768 | 0.9792 | 0.9840 | 0.9888 |
| PBA | 18.0000 | 18.0000 | 18.0000 | 18.0000 | 18.0000 | 18.0000 |
| PMA | 20.0000 | 20.0000 | 20.0000 | 20.0000 | 20.0000 | 20.0000 |
| PDTPBL | 450.00 | 450.00 | 450.00 | 450.00 | 450.00 | 450.00 |
| PDTPML | 500.00 | 657.88 | 862.06 | 961.51 | 1249.97 | 1785.67 |
| ITDPL | 0.1111 | 0.4620 | 0.9157 | 1.1367 | 1.7777 | 2.9681 |
| ICPA | 0.9300 | 0.9300 | 0.9300 | 0.9300 | 0.9300 | 0.9300 |
| CETDPL | 0.1195 | 0.4967 | 0.9846 | 1.2223 | 1.9115 | 3.1916 |
| ----- | | | | | | |
| DAA | -0.9300 | -0.9300 | -0.9300 | -0.9300 | -0.9300 | -0.9300 |
| SBA | 0.9600 | 0.9600 | 0.9600 | 0.9600 | 0.9600 | 0.9600 |
| DSA | 0.0000 | -0.0100 | -0.0175 | -0.0200 | -0.0250 | -0.0300 |
| SMA | 0.9600 | 0.9696 | 0.9768 | 0.9792 | 0.9840 | 0.9888 |
| PBA | 18.0000 | 18.0000 | 18.0000 | 18.0000 | 18.0000 | 18.0000 |
| PMA | 20.5000 | 20.5000 | 20.5000 | 20.5000 | 20.5000 | 20.5000 |
| PDTPBL | 450.00 | 450.00 | 450.00 | 450.00 | 450.00 | 450.00 |
| PDTPML | 512.50 | 674.33 | 883.61 | 985.55 | 1281.22 | 1830.31 |
| ITDPL | 0.1389 | 0.4985 | 0.9636 | 1.1901 | 1.8472 | 3.0673 |
| ICPA | 0.9300 | 0.9300 | 0.9300 | 0.9300 | 0.9300 | 0.9300 |
| CETDPL | 0.1493 | 0.5360 | 1.0361 | 1.2797 | 1.9862 | 3.2982 |
| ----- | | | | | | |

Fig 4.11 (cont.)

| | | | | | | |
|--------|---------|---------|---------|---------|---------|---------|
| DAA | -0.9300 | -0.9300 | -0.9300 | -0.9300 | -0.9300 | -0.9300 |
| SBA | 0.9600 | 0.9600 | 0.9600 | 0.9600 | 0.9600 | 0.9600 |
| DSA | 0.0000 | -0.0100 | -0.0175 | -0.0200 | -0.0250 | -0.0300 |
| SMA | 0.9600 | 0.9696 | 0.9768 | 0.9792 | 0.9840 | 0.9888 |
| PBA | 18.0000 | 18.0000 | 18.0000 | 18.0000 | 18.0000 | 18.0000 |
| PMA | 21.0000 | 21.0000 | 21.0000 | 21.0000 | 21.0000 | 21.0000 |
| PDTPBL | 450.00 | 450.00 | 450.00 | 450.00 | 450.00 | 450.00 |
| PDTPML | 525.00 | 690.77 | 905.17 | 1009.59 | 1312.47 | 1874.95 |
| ITDPL | 0.1667 | 0.5351 | 1.0115 | 1.2435 | 1.9166 | 3.1666 |
| ICPA | 0.9300 | 0.9300 | 0.9300 | 0.9300 | 0.9300 | 0.9300 |
| CETDPL | 0.1792 | 0.5753 | 1.0876 | 1.3371 | 2.0609 | 3.4049 |
| ----- | | | | | | |
| DAA | -0.9300 | -0.9300 | -0.9300 | -0.9300 | -0.9300 | -0.9300 |
| SBA | 0.9600 | 0.9600 | 0.9600 | 0.9600 | 0.9600 | 0.9600 |
| DSA | 0.0000 | -0.0100 | -0.0175 | -0.0200 | -0.0250 | -0.0300 |
| SMA | 0.9600 | 0.9696 | 0.9768 | 0.9792 | 0.9840 | 0.9888 |
| PBA | 18.0000 | 18.0000 | 18.0000 | 18.0000 | 18.0000 | 18.0000 |
| PMA | 22.0000 | 22.0000 | 22.0000 | 22.0000 | 22.0000 | 22.0000 |
| PDTPBL | 450.00 | 450.00 | 450.00 | 450.00 | 450.00 | 450.00 |
| PDTPML | 550.00 | 723.67 | 948.27 | 1057.67 | 1374.97 | 1964.23 |
| ITDPL | 0.2222 | 0.6081 | 1.1073 | 1.3504 | 2.0555 | 3.3650 |
| ICPA | 0.9300 | 0.9300 | 0.9300 | 0.9300 | 0.9300 | 0.9300 |
| CETDPL | 0.2389 | 0.6539 | 1.1906 | 1.4520 | 2.2102 | 3.6182 |
| ----- | | | | | | |
| DAA | -0.9300 | -0.9300 | -0.9300 | -0.9300 | -0.9300 | -0.9300 |
| SBA | 0.9600 | 0.9600 | 0.9600 | 0.9600 | 0.9600 | 0.9600 |
| DSA | 0.0000 | -0.0100 | -0.0175 | -0.0200 | -0.0250 | -0.0300 |
| SMA | 0.9600 | 0.9696 | 0.9768 | 0.9792 | 0.9840 | 0.9888 |
| PBA | 18.0000 | 18.0000 | 18.0000 | 18.0000 | 18.0000 | 18.0000 |
| PMA | 23.0000 | 23.0000 | 23.0000 | 23.0000 | 23.0000 | 23.0000 |
| PDTPBL | 450.00 | 450.00 | 450.00 | 450.00 | 450.00 | 450.00 |
| PDTPML | 575.00 | 756.56 | 991.37 | 1105.74 | 1437.46 | 2053.51 |
| ITDPL | 0.2778 | 0.6812 | 1.2031 | 1.4572 | 2.1944 | 3.5634 |
| ICPA | 0.9300 | 0.9300 | 0.9300 | 0.9300 | 0.9300 | 0.9300 |
| CETDPL | 0.2987 | 0.7325 | 1.2936 | 1.5669 | 2.3595 | 3.8316 |
| ----- | | | | | | |
| DAA | -0.9300 | -0.9300 | -0.9300 | -0.9300 | -0.9300 | -0.9300 |
| SBA | 0.9600 | 0.9600 | 0.9600 | 0.9600 | 0.9600 | 0.9600 |
| DSA | 0.0000 | -0.0100 | -0.0175 | -0.0200 | -0.0250 | -0.0300 |
| SMA | 0.9600 | 0.9696 | 0.9768 | 0.9792 | 0.9840 | 0.9888 |
| PBA | 18.0000 | 18.0000 | 18.0000 | 18.0000 | 18.0000 | 18.0000 |
| PMA | 24.0000 | 24.0000 | 24.0000 | 24.0000 | 24.0000 | 24.0000 |
| PDTPBL | 450.00 | 450.00 | 450.00 | 450.00 | 450.00 | 450.00 |
| PDTPML | 600.00 | 789.45 | 1034.48 | 1153.82 | 1499.96 | 2142.80 |
| ITDPL | 0.3333 | 0.7543 | 1.2988 | 1.5640 | 2.3333 | 3.7618 |
| ICPA | 0.9300 | 0.9300 | 0.9300 | 0.9300 | 0.9300 | 0.9300 |
| CETDPL | 0.3584 | 0.8111 | 1.3966 | 1.6818 | 2.5089 | 4.0449 |
| ----- | | | | | | |

Fig 4.11 (cont.)



LEGEND: PMA *-*-* 18000 +--+ 19000 *-* 20000
 □-□-□ 21000 ◇-◇-◇ 22000 +--+ 23000
 --* 24000

FIG 4.12 ATTACK AIRCRAFT : ITDPL VS DSA

4.4), the fighter aircraft were engaged in combat with the enemy air threat platforms. To compare the performance of the aircrafts, that model would require reruns with the features of the modified and baseline aircrafts being reflected in the input parameters -- the deltas -- whereas in the present model that is not required. In this section, besides the computer simulation an analytical approach has also been presented. The measures of effectiveness are obtained using the analytical solution of the model. A computational routine has been developed to generate a series of plots that relate the inputs (deltas) and the outputs (measures of effectiveness) and thus help carry out the tradeoff analysis easily.

The theoretical basis of the model is that described earlier in Sections 4.2 and 4.4. The inputs to the model are delta survivability, delta acquisition cost, delta maintenance cost, delta payload and the survivability of the baseline aircraft. The payload of the modified aircraft can also be calculated using equation 4.43 for which delta weight would have to be the input instead of delta payload. Effectiveness increase due to payload multiplier, MFEIPM, is a variable introduced to account for the change in the effectiveness of the modified aircraft. It is used as a multiplier for the sortie rate. Combat effectiveness ratio or parameter (CER) and kill loss ratio (KLR) are two measures of effectiveness that have been added. Combat effectiveness ratio is a measure of the ratio of the effectiveness of the two forces. It gives an indication of the superiority of the forces. Combat effectiveness ratio has been defined as the square root of ratio of the effectiveness of the modified aircraft to that of the baseline aircraft. If $CER > 1$, then the modified aircraft is better under the given conditions. Kill

loss ratio is defined as the ratio of aircrafts lost by the baseline force to those lost by the modified force. In other words, it is the cumulative losses of the baseline force divided by the cumulative losses of the modified force. The fraction of the forces lost is used in the actual computation of KLR. Kill loss ratio multiplier (KLRM) is defined as the ratio of the fraction of the force lost by the baseline force to the fraction lost by the modified. Clearly, KLR is then the product of KLRM and the ratio of the initial inventory of the baseline force to that of the modified force. A value of KLRM greater than 1 indicates that the baseline force is losing aircraft faster than the modified force. Mathematically,

$$\text{KLRM} = \text{FFLBF}/\text{FFLMF} = 1/(1-\text{DPLCC}) \quad (4.44)$$

$$\text{and KLR} = (\text{FFLBF} \cdot \text{BFN}/\text{FFLMF} \cdot \text{MFN}) = \text{KLRM} \cdot (\text{BFN}/\text{MFN}) \quad (4.45)$$

$$\text{but, } \text{BFN}/\text{MFN} = 1 - \text{DAF}$$

$$\text{Therefore, } \text{KLR} = (1-\text{DAF})/(1-\text{DPLCC}) \quad (4.46)$$

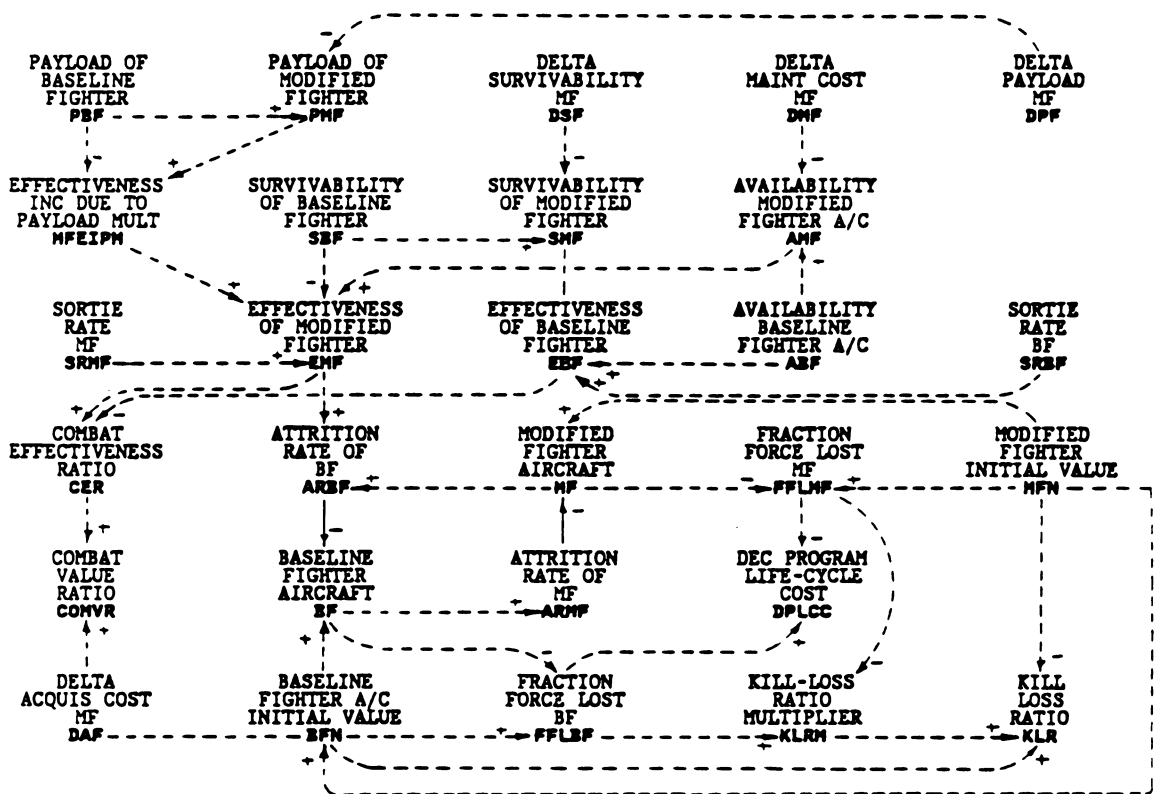
The other measures of effectiveness are obtained as explained earlier.

The computational routine is developed based on the analytical solution of the model. The salient points of the analytical solution that form the basic steps of the computational routine are shown in Table 4.3.

The causal diagram for the model is presented in Figure 4.13. The DYNAMO equations of the model and the results of the computer simulation are presented in Figures 4.14 and 4.15 respectively.

Table 4.3 Steps in the Computational Routine for Fighter Aircraft

| Parameter | Symbol | How Obtained |
|---|--------|------------------------------|
| 1. Delta Acquisition Cost | DAF | input |
| 2. Survivability of Baseline Fighter | SBF | input |
| 3. Delta Survivability | DSF | input |
| 4. Survivability of Modified Fighter | SMF | $SBF(1-DSF)$ |
| 5. Sortie Rate of Baseline Fighter | SRBF | input |
| 6. Payload of Baseline Fighter | PBF | input |
| 7. Payload of Modified Fighter | PMF | input |
| 8. Sortie rate of Modified Fighter | SRMF | $SRBF*(PMF/PBF)$ |
| 9. Availability of Baseline Fighter | ABF | input |
| 10. Availability of Modified Fighter | AMF | $ABF(1-DMF)$ |
| 11. Effectiveness Parameter for Baseline Aircraft | B | $SRBF*ABF*(1-SMF)$ |
| 12. Effectiveness Parameter for Modified Aircraft | C | $SRMF*AMF*(1-SBF)$ |
| 13. Combat effectiveness Ratio | CB | $SQRT(C/B)$ |
| 14. Combat Value Ratio | COMVR | $CB/(1-DAF)$ |
| 15. Constant 1 | C1 | $COTH^{-1}(COMVR)$ |
| 16. Constant X | X | $COSH(COTH^{-1}COMVR)$ |
| 17. Constant 2 | C2 | $SINH(COTH^{-1}COMVR)$ |
| 18. Constant Y | Y | $SINH(COTH^{-1}COMVR)/COMVR$ |
| 19. Decreased Program Life Cycle Cost | DPLCC | X-Y |
| 20. Kill Loss Ratio | KLR | $(1-DAF)/(1-DPLCC)$ |



CAUSAL DIAGRAM FOR SURVIVABILITY TRADEOFF - FIGHTER AIRCRAFT
 Fig 4.13

```

*****
*                SURVIVABILITY TRADEOFF ANALYSIS                *
*                FOR REPLACEMENT OF                              *
*  FIGHTER AIRCRAFT BF WITH MODIFIED FIGHTER AIRCRAFT MF      *
*****

```

```

L   MF.K=MF.J-(DT)(ARMF.JK)
N   MF=MFN
NOTE MF - AIRCRAFT MF INVENTORY
N   MFN=NAC*ARC*FPC
NOTE MFN - AIRCRAFT MF INVENTORY INITIAL VALUE
C   NAC=15
NOTE NAC - NUMBER OF AIRCRAFT CARRIERS
C   ARC=1.5
NOTE ARC - ATTRITION REPLACEMENT CONSTANT
C   FPC=24
NOTE FPC - FIGHTER AIRCRAFT PER CARRIER
R   ARMF.KL=BF.K*B
NOTE ARMF - ATTRITION RATE FOR AIRCRAFT MF
N   B=SRBF*ABF*(1-SMF)
NOTE B - EFFECTIVENESS PARAMETER FOR BF VS MF
C   ABF=0.5
C   SRBF=4
N   SMF=SBF*(1-DSF)
NOTE SMF - SURVIVABILITY OF AIRCRAFT MF
C   SBF=0.965
C   DSF=-0.017
L   BF.K=MAX(0,(BF.J-(DT)(ARBF.JK)))
N   BF=BFN
N   BFN=MFN*(1-DAF)
C   DAF=-0.33
R   ARBF.KL=MF.K*C
NOTE ARBF - ATTRITION RATE FOR AIRCRAFT BF
N   C=SRMF*AMF*(1-SBF)*MFEIPM
NOTE C - EFFECTIVENESS PARAMETER FOR MF VS BF
C   SRMF=4
NOTE SRMF - EFFECTIVE SORTIE RATE FOR AIRCRAFT MF
N   AMF=ABF*(1-DMF)
NOTE AMF - AVAILABILITY OF AIRCRAFT MF
N   MFEIPM=PMF/PBF
NOTE MFEIPM - MF EFFECTIVENESS INC. DUE TO PAYLOAD MULTIPLIER
C   PBF=17000
NOTE PBF - PAYLOAD FOR AIRCRAFT
N   PMF=PBF*(1-DPF)
NOTE PMF - PAYLOAD FOR AIRCRAFT MF
C   DMF=0
C   DPF=-0.206

```

Fig 4.14 System Equations - Fighter Aircraft

```

A      COMVR.K=SQRT(C/B)/(1-DAF)
NOTE  COMVR - COMBAT VALUE RATIO
A      CER.K=SQRT(C/B)
NOTE  CER - COMBAT EFFECTIVENESS RATIO
A      DPLCC.K=1-(FFLMF.K/FFLF.K)
NOTE  DPLCC - DECREASED PROGRAM LIFE CYCLE COST
A      FFLMF.K=CLIP(.01,(MFN-MF.K)/MFN,MF.K,MFN)
NOTE  FFLMF - FRACTION FORCE LOST FOR AIRCRAFT MF
A      FFLF.K=CLIP(.01,(BFN-BF.K)/BFN,BF.K,BFN)
NOTE  FFLF - FRACTION FORCE LOST FOR AIRCRAFT BF
A      KLR.K=(FFLF.K/FFLMF.K)(BFN/MFN)
NOTE  KLR - INCREASED KILL-LOSS RATIO FOR MF OVER BF
NOTE  *****
SPEC  DT=.025/PLTPER=2/PRTPER=2/LENGTH=30
PRINT MF,BF
PRINT COMVR,DPLCC,KLR,CER
PLOT  MF=M,BF=B(0,800)
RUN
QUIT

```

Fig 4.14 (cont.)

SURVIVABILITY ENHANCEMENT SCHEME 1 : DAF=-.33 DSF=-.017

| | | | |
|-------------|-------------|-----------|-----------|
| TIME=.00 | MF=540.0 | BF=718.2 | |
| COMVR=1.133 | DPLCC=.0000 | KLR=1.330 | CER=1.507 |
| TIME= 2.00 | MF=489.8 | BF=631.3 | |
| COMVR=1.133 | DPLCC=.2320 | KLR=1.732 | CER=1.507 |
| TIME= 4.00 | MF=445.8 | BF=552.3 | |
| COMVR=1.133 | DPLCC=.2446 | KLR=1.761 | CER=1.507 |
| TIME= 6.00 | MF=407.4 | BF=480.3 | |
| COMVR=1.133 | DPLCC=.2585 | KLR=1.794 | CER=1.507 |
| TIME= 8.00 | MF=374.1 | BF=414.4 | |
| COMVR=1.133 | DPLCC=.2737 | KLR=1.831 | CER=1.507 |
| TIME=10.00 | MF=345.5 | BF=353.7 | |
| COMVR=1.133 | DPLCC=.2905 | KLR=1.874 | CER=1.507 |
| TIME=12.00 | MF=321.3 | BF=297.4 | |
| COMVR=1.133 | DPLCC=.3088 | KLR=1.924 | CER=1.507 |
| TIME=14.00 | MF=301.1 | BF=244.9 | |
| COMVR=1.133 | DPLCC=.3288 | KLR=1.981 | CER=1.507 |
| TIME=16.00 | MF=284.7 | BF=195.5 | |
| COMVR=1.133 | DPLCC=.3505 | KLR=2.048 | CER=1.507 |
| TIME=18.00 | MF=271.9 | BF=148.5 | |
| COMVR=1.133 | DPLCC=.3742 | KLR=2.125 | CER=1.507 |
| TIME=20.00 | MF=262.5 | BF=103.4 | |
| COMVR=1.133 | DPLCC=.3998 | KLR=2.216 | CER=1.507 |
| TIME=22.00 | MF=256.4 | BF= 59.6 | |
| COMVR=1.133 | DPLCC=.4274 | KLR=2.323 | CER=1.507 |
| TIME=24.00 | MF=253.6 | BF= 16.6 | |
| COMVR=1.133 | DPLCC=.4571 | KLR=2.450 | CER=1.507 |
| TIME=26.00 | MF=253.3 | BF= .0 | |
| COMVR=1.133 | DPLCC=.4692 | KLR=2.505 | CER=1.507 |
| TIME=28.00 | MF=253.3 | BF= .0 | |
| COMVR=1.133 | DPLCC=.4692 | KLR=2.505 | CER=1.507 |
| TIME=30.00 | MF=253.3 | BF= .0 | |
| COMVR=1.133 | DPLCC=.4692 | KLR=2.505 | CER=1.507 |

Fig 4.15 Simulation Results - Tradeoff Analysis for Fighter Aircraft

| SURVIVABILITY ENHANCEMENT SCHEME 2 : DAF=-.25 DSF=-.014 | | | |
|---|-------------|-----------|-----------|
| TIME=.00 | MF=540.0 | BF=675.0 | |
| COMVR=1.121 | DPLCC=.0000 | KLR=1.250 | CER=1.401 |
| TIME= 2.00 | MF=485.7 | BF=588.4 | |
| COMVR=1.121 | DPLCC=.2159 | KLR=1.594 | CER=1.401 |
| TIME= 4.00 | MF=438.5 | BF=510.5 | |
| COMVR=1.121 | DPLCC=.2288 | KLR=1.621 | CER=1.401 |
| TIME= 6.00 | MF=397.6 | BF=439.9 | |
| COMVR=1.121 | DPLCC=.2430 | KLR=1.651 | CER=1.401 |
| TIME= 8.00 | MF=362.6 | BF=375.8 | |
| COMVR=1.121 | DPLCC=.2588 | KLR=1.687 | CER=1.401 |
| TIME=10.00 | MF=332.8 | BF=317.1 | |
| COMVR=1.121 | DPLCC=.2763 | KLR=1.727 | CER=1.401 |
| TIME=12.00 | MF=307.8 | BF=263.0 | |
| COMVR=1.121 | DPLCC=.2956 | KLR=1.775 | CER=1.401 |
| TIME=14.00 | MF=287.4 | BF=212.8 | |
| COMVR=1.121 | DPLCC=.3168 | KLR=1.830 | CER=1.401 |
| TIME=16.00 | MF=271.1 | BF=165.7 | |
| COMVR=1.121 | DPLCC=.3400 | KLR=1.894 | CER=1.401 |
| TIME=18.00 | MF=258.8 | BF=121.0 | |
| COMVR=1.121 | DPLCC=.3654 | KLR=1.970 | CER=1.401 |
| TIME=20.00 | MF=250.2 | BF= 78.1 | |
| COMVR=1.121 | DPLCC=.3931 | KLR=2.060 | CER=1.401 |
| TIME=22.00 | MF=245.2 | BF= 36.3 | |
| COMVR=1.121 | DPLCC=.4231 | KLR=2.167 | CER=1.401 |
| TIME=24.00 | MF=243.9 | BF= .0 | |
| COMVR=1.121 | DPLCC=.4516 | KLR=2.279 | CER=1.401 |
| TIME=26.00 | MF=243.9 | BF= .0 | |
| COMVR=1.121 | DPLCC=.4516 | KLR=2.279 | CER=1.401 |
| TIME=28.00 | MF=243.9 | BF= .0 | |
| COMVR=1.121 | DPLCC=.4516 | KLR=2.279 | CER=1.401 |
| TIME=30.00 | MF=243.9 | BF= .0 | |
| COMVR=1.121 | DPLCC=.4516 | KLR=2.279 | CER=1.401 |

Fig 4.15 (cont.)

A small computer program (in FORTRAN) has been developed and used to help in the computation of the measures of effectiveness. The program and the tabulation of the computations is presented in Figure 4.16. The manner in which the computational routine is used to obtain curves depicting the interrelationships between the various parameters and measures of effectiveness is explained next.

Table 4.3 and Figure 4.16 help bring out the relationships between the parameters, variables and measures of effectiveness. The relative combat effectiveness parameter (CER) can be expressed as a function of the delta survivability and the payload of the modified aircraft. It is thus possible to obtain a family of curves relating the relative combat effectiveness parameter to the delta survivability for different values of the payload. This relationship is shown in Figure 4.17.

It is also seen that the combat value ratio can be expressed as a function of the relative combat effectiveness parameter and the delta acquisition cost. For a specific value of COMVR, a plot of the various combinations of CER and DAF can be obtained. Thus another family of curves can be generated depicting the interrelationship between these three variables and this is shown in Figure 4.18.

Decreased program life cycle cost can be expressed as a function of the combat value ratio. This relationship is presented in Figure 4.19. It is also to be noted that the kill loss ratio multiplier and DPLCC are interrelated. This relationship will be shown on the nomograph presented later in this chapter.

DPLCC, DAF and the kill loss ratio are also interrelated. Different combinations of DAF and DPLCC are related to specific kill loss ratios,

```

C *****
C * COMPUTATIONAL ROUTINE FOR THE REPLACEMENT OF F-14 FIGHTER *
C * MODIFIED FIGHTER AIRCRAFT (ATA) *
C *****
C
REAL KLR
DIMENSION DAF(9),SBF(9),DSF(9),SMF(9),SRBF(9),PBF(9),PMF(9),
1 SRMF(9),ABF(9),AMF(9),B(9),C(9),CB(9),C1(9),X(9),C2(9),Y(9),
2 DPLCC(9),KLR(9),COMVR(9)
DPF = -.206
DMF = 0.0
READ (5,*) NDSF
READ (5,*) (DSF(IDSF),IDSF=1,NDSF)
READ (5,*) (DAF(ID),ID=1,6)
DO 9 NPMF = 1,9
DO 19 IN =1,NDSF
SBF(IN) = .965
SMF(IN) = SBF(IN) * (1-DSF(IN))
SRBF(IN) = 4.0
PBF(IN) = 17.000
PMF(IN) = PBF(IN) + NPMF -1
IF (NPMF.EQ.5) PMF(IN) = PBF(IN) + NPMF - 1.5
IF (NPMF.GT.5) PMF(IN) = PBF(IN) + NPMF - 2
SRMF(IN) = SRBF(IN) * PMF(IN) / PBF(IN)
ABF(IN) = .5
AMF(IN) = ABF(IN) * (1 - DMF)
B(IN) = SRBF(IN) * ABF(IN) * (1 - SMF(IN) )
C(IN) = SRMF(IN) * AMF(IN) * (1 - SBF(IN) )
CB(IN) = SQRT(C(IN) / B(IN) )
COMVR(IN) = CB(IN) / (1 - DAF(IN) )
IF (COMVR(IN).LE.1.0) GO TO 29
C1(IN) = 0.5 * ALOG( (COMVR(IN)+1) / (COMVR(IN)-1) )
X(IN) = COSH(C1(IN))
C2(IN) = SINH(C1(IN))
Y(IN) = C2(IN) / COMVR(IN)
DPLCC(IN) = X(IN) - Y(IN)
KLR(IN) = (1 - DAF(IN)) / (1 - DPLCC(IN))
GO TO 19
29 C1(IN) = 0.0
X(IN) = 0.0
C2(IN) = 0.0
Y(IN) = 0.0
DPLCC(IN) = 0.0
KLR(IN) = 0.0
19 CONTINUE
WRITE(6,200) (DAF(IN),IN=1,NDSF)
WRITE(6,210) (SBF(IN),IN=1,NDSF)
WRITE(6,220) (DSF(IN),IN=1,NDSF)
WRITE(6,230) (SMF(IN),IN=1,NDSF)

```

Fig 4.16 Computational Routine for Fighter Aircraft

```

WRITE(6,240) (SRBF(IN),IN=1,NDSF)
WRITE(6,250) (PBF(IN),IN=1,NDSF)
WRITE(6,260) (PMF(IN),IN=1,NDSF)
WRITE(6,270) (SRMF(IN),IN=1,NDSF)
WRITE(6,280) (ABF(IN),IN=1,NDSF)
WRITE(6,290) (AMF(IN),IN=1,NDSF)
WRITE(6,300) (B(IN),IN=1,NDSF)
WRITE(6,310) (C(IN),IN=1,NDSF)
WRITE(6,320) (CB(IN),IN=1,NDSF)
WRITE(6,330)
WRITE(6,340) (COMVR(IN),IN=1,NDSF)
WRITE(6,350) (C1(IN),IN=1,NDSF)
WRITE(6,360) (X(IN),IN=1,NDSF)
WRITE(6,370) (C2(IN),IN=1,NDSF)
WRITE(6,380) (Y(IN),IN=1,NDSF)
WRITE(6,390) (DPLCC(IN),IN=1,NDSF)
WRITE(6,400) (KLR(IN),IN=1,NDSF)
200  FORMAT(5X,'DAF',5X,6(F8.4,2X) )
210  FORMAT(5X,'SBF',5X,6(F8.4,2X) )
220  FORMAT(5X,'DSF',5X,6(F8.4,2X) )
230  FORMAT(5X,'SMF',5X,6(F8.4,2X) )
240  FORMAT(5X,'SRBF',4X,6(F8.4,2X) )
250  FORMAT(5X,'PBF',5X,6(F8.4,2X) )
260  FORMAT(5X,'PMF',5X,6(F8.4,2X) )
270  FORMAT(5X,'SRMF',4X,6(F8.2,2X) )
280  FORMAT(5X,'ABF',5X,6(F8.4,2X) )
290  FORMAT(5X,'AMF',5X,6(F8.4,2X) )
300  FORMAT(5X,'B',7X,6(F8.4,2X) )
310  FORMAT(5X,'C',7X,6(F8.4,2X) )
320  FORMAT(5X,'CB',6X,6(F8.4,2X) )
330  FORMAT(5X)
340  FORMAT(5X,'COMVR',3X,6(F8.4,2X) )
350  FORMAT(5X,'C1',6X,6(F8.4,2X) )
360  FORMAT(5X,'X',7X,6(F8.4,2X) )
370  FORMAT(5X,'C2',6X,6(F8.4,2X) )
380  FORMAT(5X,'Y',7X,6(F8.4,2X) )
390  FORMAT(5X,'DPLCC',3X,6(F8.4,2X) )
400  FORMAT(5X,'KLR',5X,6(F8.4,2X) / 3X,70('-') )
9    CONTINUE
    STOP
    END

6
0, -.01, -.0170, -.02, -.025, -.03
-.330, -.330, -.330, -.330, -.330, -.330

```

Fig 4.16 (cont.)

| | | | | | | |
|-------|---------|---------|---------|---------|---------|---------|
| DAF | -0.3300 | -0.3300 | -0.3300 | -0.3300 | -0.3300 | -0.3300 |
| SBF | 0.9650 | 0.9650 | 0.9650 | 0.9650 | 0.9650 | 0.9650 |
| DSF | 0.0000 | -0.0100 | -0.0170 | -0.0200 | -0.0250 | -0.0300 |
| SMF | 0.9650 | 0.9746 | 0.9814 | 0.9843 | 0.9891 | 0.9939 |
| SRBF | 4.0000 | 4.0000 | 4.0000 | 4.0000 | 4.0000 | 4.0000 |
| PBF | 17.0000 | 17.0000 | 17.0000 | 17.0000 | 17.0000 | 17.0000 |
| PMF | 17.0000 | 17.0000 | 17.0000 | 17.0000 | 17.0000 | 17.0000 |
| SRMF | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 |
| ABF | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 |
| AMF | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 |
| B | 0.0700 | 0.0507 | 0.0372 | 0.0314 | 0.0218 | 0.0121 |
| C | 0.0700 | 0.0700 | 0.0700 | 0.0700 | 0.0700 | 0.0700 |
| CB | 1.0000 | 1.1750 | 1.3719 | 1.4931 | 1.7940 | 2.4052 |
| COMVR | 0.7519 | 0.8835 | 1.0315 | 1.1226 | 1.3488 | 1.8084 |
| C1 | 0.0000 | 0.0000 | 2.0831 | 1.4257 | 0.9535 | 0.6227 |
| X | 0.0000 | 0.0000 | 4.0768 | 2.2006 | 1.4901 | 1.2002 |
| C2 | 0.0000 | 0.0000 | 3.9523 | 1.9603 | 1.1047 | 0.6637 |
| Y | 0.0000 | 0.0000 | 3.8316 | 1.7462 | 0.8190 | 0.3670 |
| DPLCC | 0.0000 | 0.0000 | 0.2453 | 0.4544 | 0.6711 | 0.8332 |
| KLR | 0.0000 | 0.0000 | 1.7623 | 2.4378 | 4.0436 | 7.9735 |

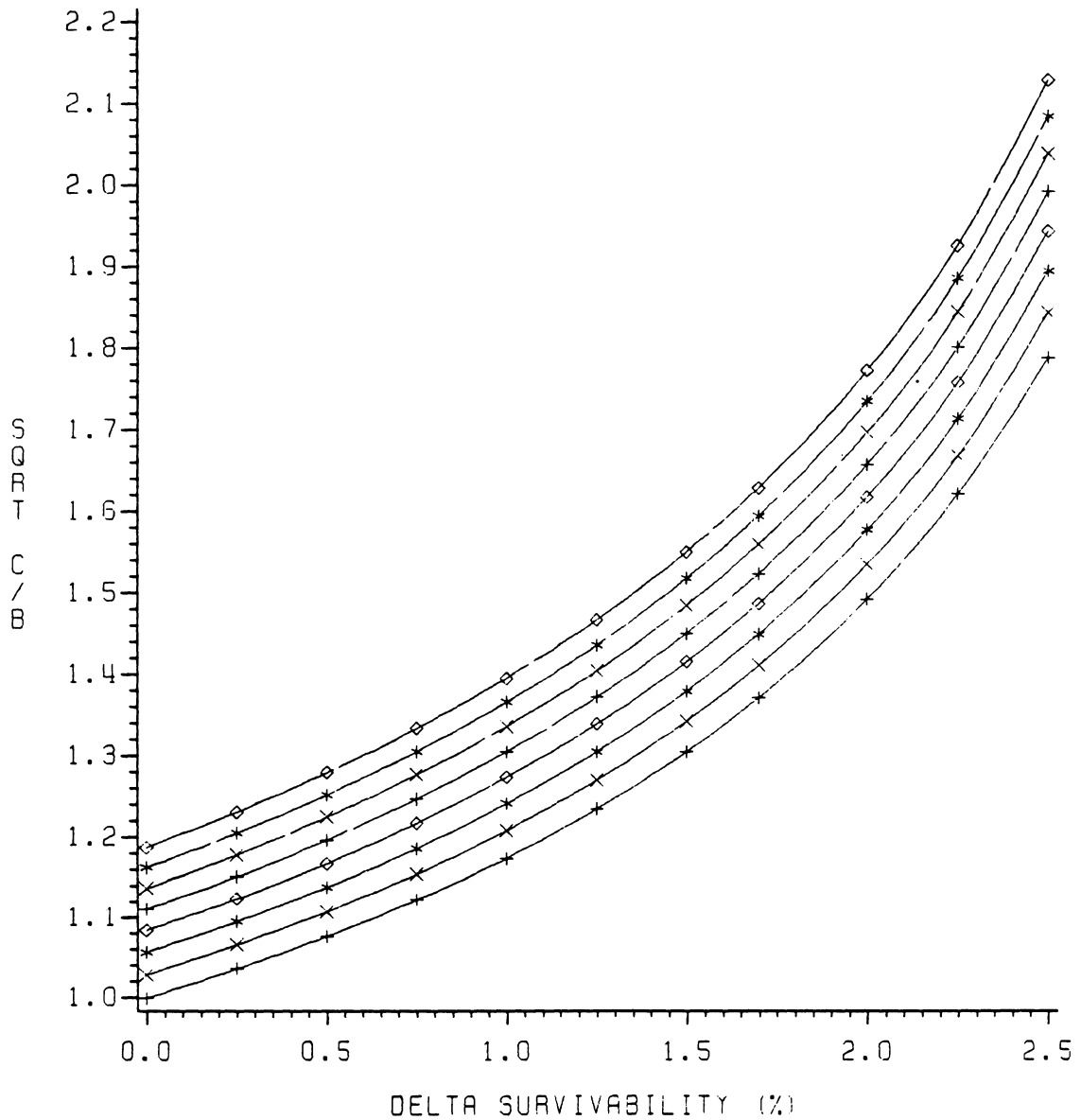
| | | | | | | |
|-------|---------|---------|---------|---------|---------|---------|
| DAF | -0.3300 | -0.3300 | -0.3300 | -0.3300 | -0.3300 | -0.3300 |
| SBF | 0.9650 | 0.9650 | 0.9650 | 0.9650 | 0.9650 | 0.9650 |
| DSF | 0.0000 | -0.0100 | -0.0170 | -0.0200 | -0.0250 | -0.0300 |
| SMF | 0.9650 | 0.9746 | 0.9814 | 0.9843 | 0.9891 | 0.9939 |
| SRBF | 4.0000 | 4.0000 | 4.0000 | 4.0000 | 4.0000 | 4.0000 |
| PBF | 17.0000 | 17.0000 | 17.0000 | 17.0000 | 17.0000 | 17.0000 |
| PMF | 18.0000 | 18.0000 | 18.0000 | 18.0000 | 18.0000 | 18.0000 |
| SRMF | 4.24 | 4.24 | 4.24 | 4.24 | 4.24 | 4.24 |
| ABF | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 |
| AMF | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 |
| B | 0.0700 | 0.0507 | 0.0372 | 0.0314 | 0.0218 | 0.0121 |
| C | 0.0741 | 0.0741 | 0.0741 | 0.0741 | 0.0741 | 0.0741 |
| CB | 1.0290 | 1.2091 | 1.4117 | 1.5363 | 1.8460 | 2.4749 |
| COMVR | 0.7737 | 0.9091 | 1.0614 | 1.1551 | 1.3879 | 1.8608 |
| C1 | 0.0000 | 0.0000 | 1.7567 | 1.3156 | 0.9087 | 0.6005 |
| X | 0.0000 | 0.0000 | 2.9830 | 1.9977 | 1.4420 | 1.1858 |
| C2 | 0.0000 | 0.0000 | 2.8104 | 1.7294 | 1.0390 | 0.6372 |
| Y | 0.0000 | 0.0000 | 2.6478 | 1.4971 | 0.7486 | 0.3424 |
| DPLCC | 0.0000 | 0.0000 | 0.3352 | 0.5006 | 0.6935 | 0.8433 |
| KLR | 0.0000 | 0.0000 | 2.0007 | 2.6631 | 4.3388 | 8.4892 |

| | | | | | | |
|------|---------|---------|---------|---------|---------|---------|
| DAF | -0.3300 | -0.3300 | -0.3300 | -0.3300 | -0.3300 | -0.3300 |
| SBF | 0.9650 | 0.9650 | 0.9650 | 0.9650 | 0.9650 | 0.9650 |
| DSF | 0.0000 | -0.0100 | -0.0170 | -0.0200 | -0.0250 | -0.0300 |
| SMF | 0.9650 | 0.9746 | 0.9814 | 0.9843 | 0.9891 | 0.9939 |
| SRBF | 4.0000 | 4.0000 | 4.0000 | 4.0000 | 4.0000 | 4.0000 |
| PBF | 17.0000 | 17.0000 | 17.0000 | 17.0000 | 17.0000 | 17.0000 |
| PMF | 19.0000 | 19.0000 | 19.0000 | 19.0000 | 19.0000 | 19.0000 |
| SRMF | 4.47 | 4.47 | 4.47 | 4.47 | 4.47 | 4.47 |
| ABF | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 |

| | | | | | | |
|-------|---------|---------|---------|---------|---------|---------|
| AMF | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 |
| B | 0.0700 | 0.0507 | 0.0372 | 0.0314 | 0.0218 | 0.0121 |
| C | 0.0782 | 0.0782 | 0.0782 | 0.0782 | 0.0782 | 0.0782 |
| CB | 1.0572 | 1.2422 | 1.4504 | 1.5784 | 1.8965 | 2.5427 |
| COMVR | 0.7949 | 0.9340 | 1.0905 | 1.1868 | 1.4260 | 1.9118 |
| C1 | 0.0000 | 0.0000 | 1.5699 | 1.2301 | 0.8698 | 0.5805 |
| X | 0.0000 | 0.0000 | 2.5071 | 1.8569 | 1.4027 | 1.1733 |
| C2 | 0.0000 | 0.0000 | 2.2990 | 1.5646 | 0.9837 | 0.6137 |
| Y | 0.0000 | 0.0000 | 2.1082 | 1.3183 | 0.6898 | 0.3210 |
| DPLCC | 0.0000 | 0.0000 | 0.3989 | 0.5385 | 0.7129 | 0.8523 |
| KLR | 0.0000 | 0.0000 | 2.2125 | 2.8821 | 4.6324 | 9.0044 |
| ----- | | | | | | |
| DAF | -0.3300 | -0.3300 | -0.3300 | -0.3300 | -0.3300 | -0.3300 |
| SBF | 0.9650 | 0.9650 | 0.9650 | 0.9650 | 0.9650 | 0.9650 |
| DSF | 0.0000 | -0.0100 | -0.0170 | -0.0200 | -0.0250 | -0.0300 |
| SMF | 0.9650 | 0.9746 | 0.9814 | 0.9843 | 0.9891 | 0.9939 |
| SRBF | 4.0000 | 4.0000 | 4.0000 | 4.0000 | 4.0000 | 4.0000 |
| PBF | 17.0000 | 17.0000 | 17.0000 | 17.0000 | 17.0000 | 17.0000 |
| PMF | 20.0000 | 20.0000 | 20.0000 | 20.0000 | 20.0000 | 20.0000 |
| SRMF | 4.71 | 4.71 | 4.71 | 4.71 | 4.71 | 4.71 |
| ABF | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 |
| AMF | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 |
| B | 0.0700 | 0.0507 | 0.0372 | 0.0314 | 0.0218 | 0.0121 |
| C | 0.0824 | 0.0824 | 0.0824 | 0.0824 | 0.0824 | 0.0824 |
| CB | 1.0847 | 1.2745 | 1.4880 | 1.6194 | 1.9458 | 2.6088 |
| COMVR | 0.8155 | 0.9582 | 1.1188 | 1.2176 | 1.4630 | 1.9615 |
| C1 | 0.0000 | 0.0000 | 1.4405 | 1.1607 | 0.8357 | 0.5625 |
| X | 0.0000 | 0.0000 | 2.2297 | 1.7527 | 1.3700 | 1.1624 |
| C2 | 0.0000 | 0.0000 | 1.9929 | 1.4394 | 0.9364 | 0.5926 |
| Y | 0.0000 | 0.0000 | 1.7812 | 1.1822 | 0.6401 | 0.3021 |
| DPLCC | 0.0000 | 0.0000 | 0.4485 | 0.5705 | 0.7299 | 0.8603 |
| KLR | 0.0000 | 0.0000 | 2.4116 | 3.0969 | 4.9247 | 9.5192 |
| ----- | | | | | | |
| DAF | -0.3300 | -0.3300 | -0.3300 | -0.3300 | -0.3300 | -0.3300 |
| SBF | 0.9650 | 0.9650 | 0.9650 | 0.9650 | 0.9650 | 0.9650 |
| DSF | 0.0000 | -0.0100 | -0.0170 | -0.0200 | -0.0250 | -0.0300 |
| SMF | 0.9650 | 0.9746 | 0.9814 | 0.9843 | 0.9891 | 0.9939 |
| SRBF | 4.0000 | 4.0000 | 4.0000 | 4.0000 | 4.0000 | 4.0000 |
| PBF | 17.0000 | 17.0000 | 17.0000 | 17.0000 | 17.0000 | 17.0000 |
| PMF | 20.5000 | 20.5000 | 20.5000 | 20.5000 | 20.5000 | 20.5000 |
| SRMF | 4.82 | 4.82 | 4.82 | 4.82 | 4.82 | 4.82 |
| ABF | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 |
| AMF | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 |
| B | 0.0700 | 0.0507 | 0.0372 | 0.0314 | 0.0218 | 0.0121 |
| C | 0.0844 | 0.0844 | 0.0844 | 0.0844 | 0.0844 | 0.0844 |
| CB | 1.0981 | 1.2903 | 1.5065 | 1.6396 | 1.9700 | 2.6412 |
| COMVR | 0.8257 | 0.9702 | 1.1327 | 1.2328 | 1.4812 | 1.9859 |
| C1 | 0.0000 | 0.0000 | 1.3884 | 1.1305 | 0.8201 | 0.5541 |
| X | 0.0000 | 0.0000 | 2.1290 | 1.7100 | 1.3556 | 1.1575 |
| C2 | 0.0000 | 0.0000 | 1.8795 | 1.3872 | 0.9152 | 0.5829 |
| Y | 0.0000 | 0.0000 | 1.6593 | 1.1252 | 0.6179 | 0.2935 |

| | | | | | | |
|-------|---------|---------|---------|---------|---------|---------|
| DPLCC | 0.0000 | 0.0000 | 0.4697 | 0.5848 | 0.7377 | 0.8640 |
| KLR | 0.0000 | 0.0000 | 2.5081 | 3.2031 | 5.0705 | 9.7764 |
| ----- | | | | | | |
| DAF | -0.3300 | -0.3300 | -0.3300 | -0.3300 | -0.3300 | -0.3300 |
| SBF | 0.9650 | 0.9650 | 0.9650 | 0.9650 | 0.9650 | 0.9650 |
| DSF | 0.0000 | -0.0100 | -0.0170 | -0.0200 | -0.0250 | -0.0300 |
| SMF | 0.9650 | 0.9746 | 0.9814 | 0.9843 | 0.9891 | 0.9939 |
| SRBF | 4.0000 | 4.0000 | 4.0000 | 4.0000 | 4.0000 | 4.0000 |
| PBF | 17.0000 | 17.0000 | 17.0000 | 17.0000 | 17.0000 | 17.0000 |
| PMF | 21.0000 | 21.0000 | 21.0000 | 21.0000 | 21.0000 | 21.0000 |
| SRMF | 4.94 | 4.94 | 4.94 | 4.94 | 4.94 | 4.94 |
| ABF | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 |
| AMF | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 |
| B | 0.0700 | 0.0507 | 0.0372 | 0.0314 | 0.0218 | 0.0121 |
| C | 0.0865 | 0.0865 | 0.0865 | 0.0865 | 0.0865 | 0.0865 |
| CB | 1.1114 | 1.3059 | 1.5248 | 1.6594 | 1.9939 | 2.6732 |
| COMVR | 0.8357 | 0.9819 | 1.1465 | 1.2477 | 1.4991 | 2.0099 |
| C1 | 0.0000 | 0.0000 | 1.3424 | 1.1027 | 0.8054 | 0.5460 |
| X | 0.0000 | 0.0000 | 2.0447 | 1.6722 | 1.3423 | 1.1528 |
| C2 | 0.0000 | 0.0000 | 1.7835 | 1.3402 | 0.8953 | 0.5736 |
| Y | 0.0000 | 0.0000 | 1.5557 | 1.0741 | 0.5972 | 0.2854 |
| DPLCC | 0.0000 | 0.0000 | 0.4891 | 0.5980 | 0.7450 | 0.8674 |
| KLR | 0.0000 | 0.0000 | 2.6031 | 3.3087 | 5.2160 | 10.0336 |
| ----- | | | | | | |
| DAF | -0.3300 | -0.3300 | -0.3300 | -0.3300 | -0.3300 | -0.3300 |
| SBF | 0.9650 | 0.9650 | 0.9650 | 0.9650 | 0.9650 | 0.9650 |
| DSF | 0.0000 | -0.0100 | -0.0170 | -0.0200 | -0.0250 | -0.0300 |
| SMF | 0.9650 | 0.9746 | 0.9814 | 0.9843 | 0.9891 | 0.9939 |
| SRBF | 4.0000 | 4.0000 | 4.0000 | 4.0000 | 4.0000 | 4.0000 |
| PBF | 17.0000 | 17.0000 | 17.0000 | 17.0000 | 17.0000 | 17.0000 |
| PMF | 22.0000 | 22.0000 | 22.0000 | 22.0000 | 22.0000 | 22.0000 |
| SRMF | 5.18 | 5.18 | 5.18 | 5.18 | 5.18 | 5.18 |
| ABF | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 |
| AMF | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 |
| B | 0.0700 | 0.0507 | 0.0372 | 0.0314 | 0.0218 | 0.0121 |
| C | 0.0906 | 0.0906 | 0.0906 | 0.0906 | 0.0906 | 0.0906 |
| CB | 1.1376 | 1.3367 | 1.5607 | 1.6985 | 2.0408 | 2.7361 |
| COMVR | 0.8553 | 1.0050 | 1.1734 | 1.2771 | 1.5344 | 2.0572 |
| C1 | 0.0000 | 2.9953 | 1.2641 | 1.0532 | 0.7783 | 0.5309 |
| X | 0.0000 | 10.0203 | 1.9112 | 1.6078 | 1.3184 | 1.1443 |
| C2 | 0.0000 | 9.9703 | 1.6287 | 1.2590 | 0.8592 | 0.5562 |
| Y | 0.0000 | 9.9205 | 1.3880 | 0.9859 | 0.5600 | 0.2704 |
| DPLCC | 0.0000 | 0.0998 | 0.5232 | 0.6220 | 0.7585 | 0.8739 |
| KLR | 0.0000 | 1.4774 | 2.7896 | 3.5182 | 5.5065 | 10.5478 |
| ----- | | | | | | |
| DAF | -0.3300 | -0.3300 | -0.3300 | -0.3300 | -0.3300 | -0.3300 |
| SBF | 0.9650 | 0.9650 | 0.9650 | 0.9650 | 0.9650 | 0.9650 |
| DSF | 0.0000 | -0.0100 | -0.0170 | -0.0200 | -0.0250 | -0.0300 |
| SMF | 0.9650 | 0.9746 | 0.9814 | 0.9843 | 0.9891 | 0.9939 |
| SRBF | 4.0000 | 4.0000 | 4.0000 | 4.0000 | 4.0000 | 4.0000 |
| PBF | 17.0000 | 17.0000 | 17.0000 | 17.0000 | 17.0000 | 17.0000 |

| | | | | | | |
|-------|---------|---------|---------|---------|---------|---------|
| PMF | 23.0000 | 23.0000 | 23.0000 | 23.0000 | 23.0000 | 23.0000 |
| SRMF | 5.41 | 5.41 | 5.41 | 5.41 | 5.41 | 5.41 |
| ABF | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 |
| AMF | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 |
| B | 0.0700 | 0.0507 | 0.0372 | 0.0314 | 0.0218 | 0.0121 |
| C | 0.0947 | 0.0947 | 0.0947 | 0.0947 | 0.0947 | 0.0947 |
| CB | 1.1632 | 1.3667 | 1.5958 | 1.7367 | 2.0867 | 2.7976 |
| COMVR | 0.8746 | 1.0276 | 1.1998 | 1.3058 | 1.5689 | 2.1035 |
| C1 | 0.0000 | 2.1483 | 1.1994 | 1.0102 | 0.7538 | 0.5170 |
| X | 0.0000 | 4.3435 | 1.8097 | 1.5551 | 1.2978 | 1.1367 |
| C2 | 0.0000 | 4.2268 | 1.5083 | 1.1910 | 0.8272 | 0.5404 |
| Y | 0.0000 | 4.1133 | 1.2571 | 0.9121 | 0.5272 | 0.2569 |
| DPLCC | 0.0000 | 0.2302 | 0.5526 | 0.6430 | 0.7705 | 0.8798 |
| KLR | 0.0000 | 1.7278 | 2.9726 | 3.7259 | 5.7964 | 11.0617 |
| ----- | | | | | | |
| DAF | -0.3300 | -0.3300 | -0.3300 | -0.3300 | -0.3300 | -0.3300 |
| SBF | 0.9650 | 0.9650 | 0.9650 | 0.9650 | 0.9650 | 0.9650 |
| DSF | 0.0000 | -0.0100 | -0.0170 | -0.0200 | -0.0250 | -0.0300 |
| SMF | 0.9650 | 0.9746 | 0.9814 | 0.9843 | 0.9891 | 0.9939 |
| SRBF | 4.0000 | 4.0000 | 4.0000 | 4.0000 | 4.0000 | 4.0000 |
| PBF | 17.0000 | 17.0000 | 17.0000 | 17.0000 | 17.0000 | 17.0000 |
| PMF | 24.0000 | 24.0000 | 24.0000 | 24.0000 | 24.0000 | 24.0000 |
| SRMF | 5.65 | 5.65 | 5.65 | 5.65 | 5.65 | 5.65 |
| ABF | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 |
| AMF | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 |
| B | 0.0700 | 0.0507 | 0.0372 | 0.0314 | 0.0218 | 0.0121 |
| C | 0.0988 | 0.0988 | 0.0988 | 0.0988 | 0.0988 | 0.0988 |
| CB | 1.1882 | 1.3961 | 1.6301 | 1.7740 | 2.1315 | 2.8578 |
| COMVR | 0.8934 | 1.0497 | 1.2256 | 1.3338 | 1.6027 | 2.1487 |
| C1 | 0.0000 | 1.8597 | 1.1445 | 0.9723 | 0.7315 | 0.5042 |
| X | 0.0000 | 3.2886 | 1.7296 | 1.5111 | 1.2797 | 1.1298 |
| C2 | 0.0000 | 3.1329 | 1.4112 | 1.1329 | 0.7985 | 0.5258 |
| Y | 0.0000 | 2.9846 | 1.1514 | 0.8493 | 0.4982 | 0.2447 |
| DPLCC | 0.0000 | 0.3041 | 0.5782 | 0.6618 | 0.7815 | 0.8851 |
| KLR | 0.0000 | 1.9111 | 3.1530 | 3.9322 | 6.0856 | 11.5754 |
| ----- | | | | | | |



LEGEND: PYLOAD

+ + + 17000
 ◊ ◊ ◊ 20000
 * * * 23000

* * * 18000
 + + + 21000
 ◊ ◊ ◊ 24000

* * * 19000
 * * * 22000

FIG 4.17 FIGHTER AIRCRAFT : CB VS DSF

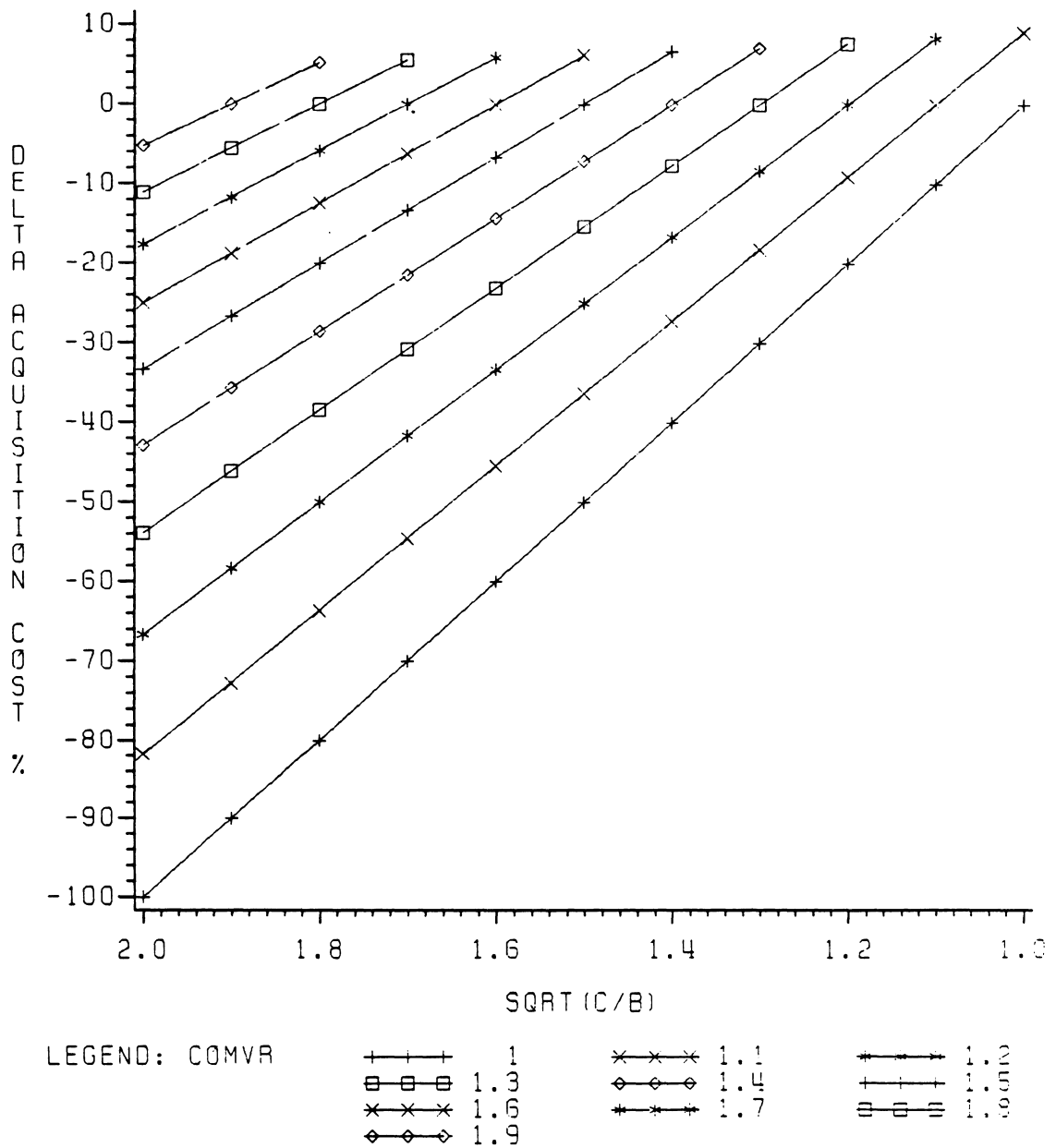


FIG 4.18 FIGHTER AIRCRAFT : DAF VS CB

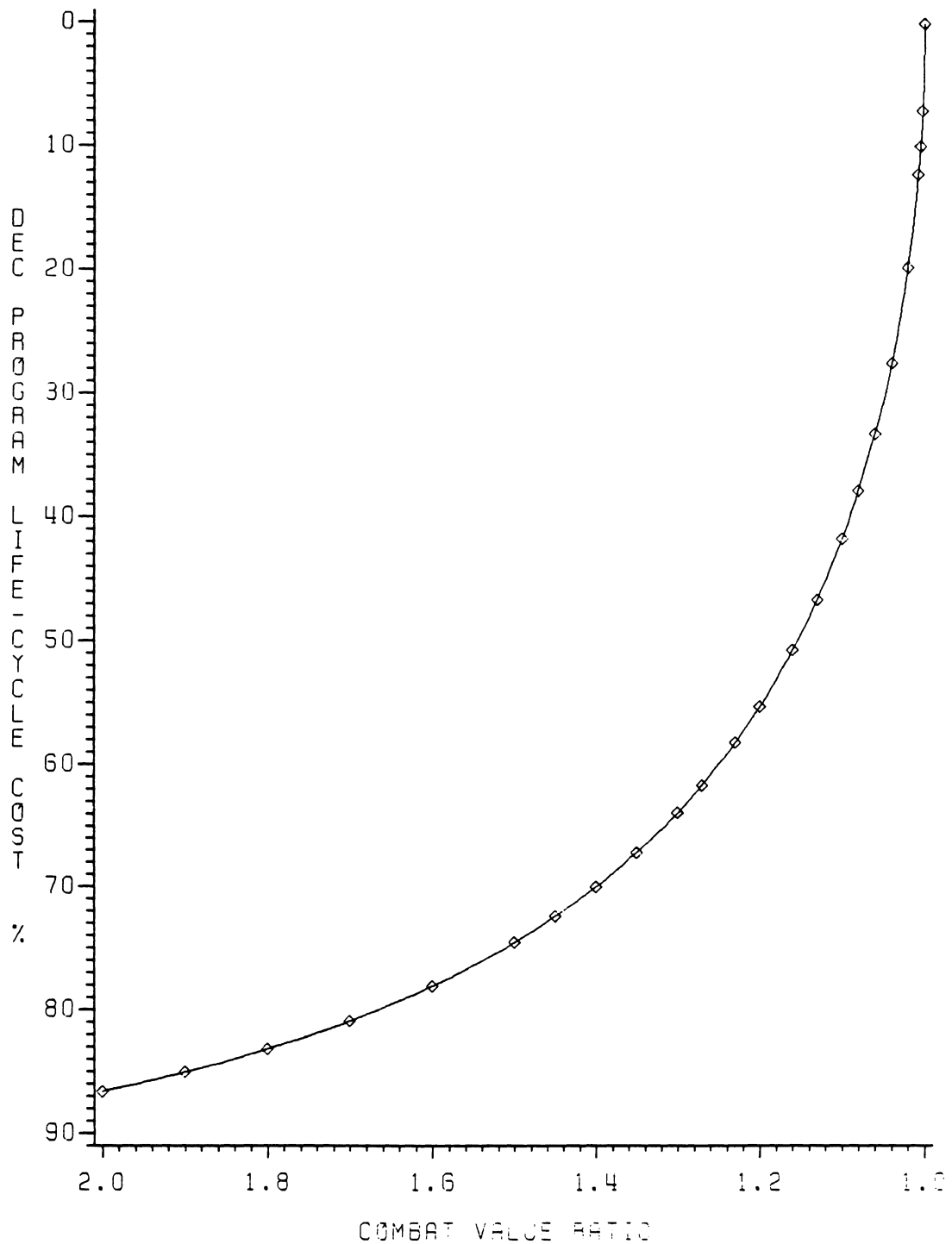
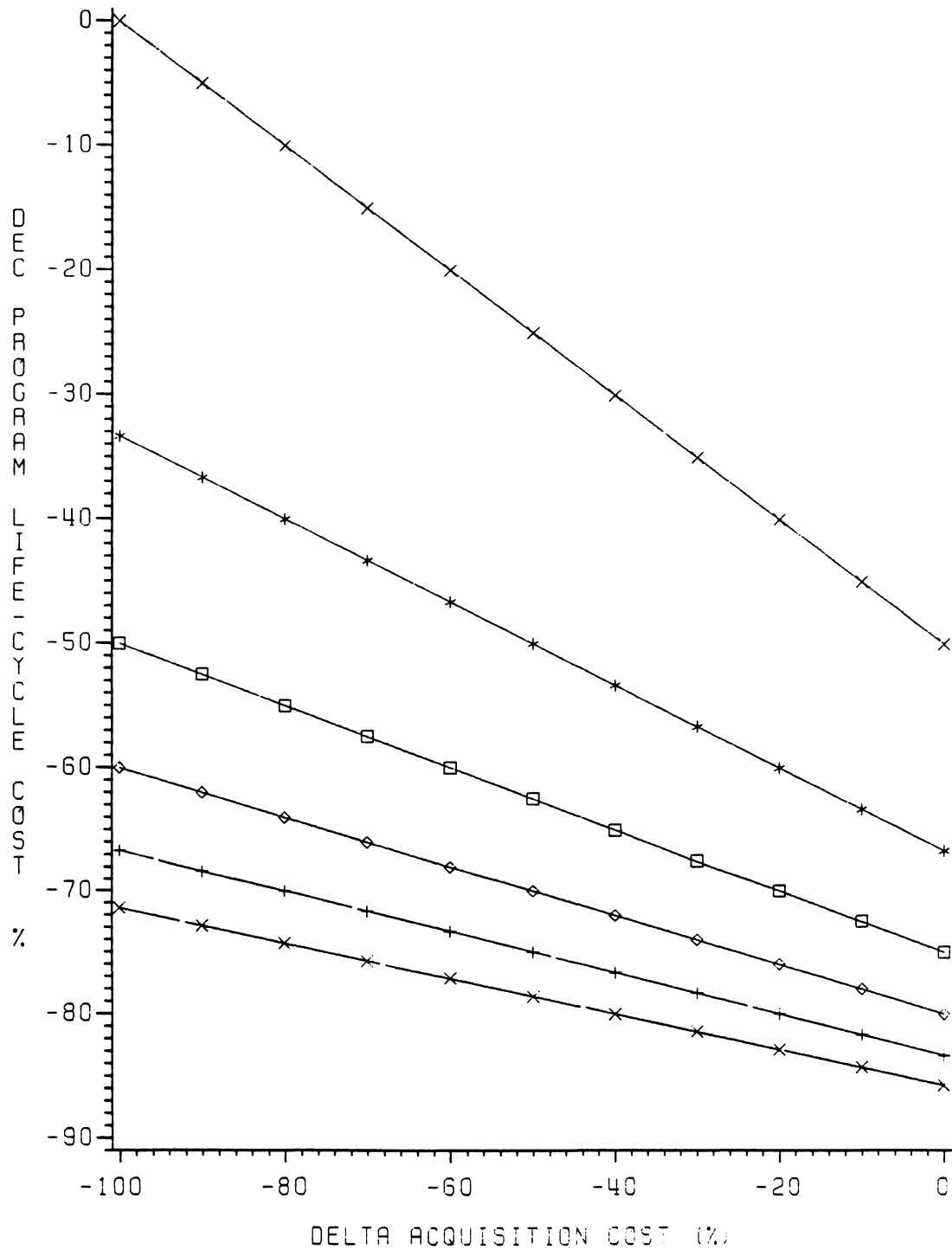


FIG 4.19 FIGHTER AIRCRAFT : DPLCC VS COMVR



LEGEND: KLF * * * * * 2 * * * * * 3 = = = = = 4
 ◇ ◇ ◇ ◇ ◇ 5 + + + + + 6 x x x x x 7

FIG 4.20 FIGHTER AIRCRAFT : DPLCC VS DAF

i.e., it is possible to plot DPLCC vs DAF to obtain a locus of KLR. This can be extended to obtain a family of curves that is shown in Figure 4.20.

4.8 ILLUSTRATION OF SURVIVABILITY TRADEOFF ANALYSIS FOR 3 TYPES OF MISSIONS

In this section, a nomograph is developed to assist survivability tradeoff analysis. This is done by interrelating the parameters and effectiveness measures involved in the tradeoff analysis. In order to do this, the curves presented in Sections 4.6 and 4.7 are made use of.

The nomograph is particularly applicable to multi-mission aircrafts, such as the proposed advanced tactical aircraft. Typically, these would be pertinent as carrier based aircrafts. However it can be used for single mission aircrafts too. The three missions considered are: (1) Attack, interdiction role (2) Fighter, air superiority role and (3) carrier defense role.

Figures 4.12, 4.17 to 4.20 are combined together to obtain the portion of the nomograph pertaining to the attack and fighter roles. In linking them together small modifications have also been made. The method by which portion of the nomograph pertaining to the carrier defense mission has been obtained is explained next.

The decrease in missile hits on aircraft carrier (DMHC) can be defined as a delta. It is the difference between the cumulative hits per loss of the modified aircraft (CHPLM) and the cumulative hits per loss of the baseline aircraft (CHPLB) divided by CHPLB.

$$\text{i.e., DMHC} = (\text{CHPLM} - \text{CHPLB}) / \text{CHPLB} \quad (4.47)$$

But CHPLM can be written in terms of the modified aircraft's probability of kill (MPK) and the probability of the modified aircraft being hit (PHM) as

$$\text{CHPLM} = \text{PHM}/\text{MPK} \quad (4.48)$$

Similarly $\text{CHPLB} = \text{PHB}/\text{BPK}$ (4.49)

where PHB = probability of hit of baseline aircraft

and BPK = baseline aircrafts probability of kill.

Thus, $\text{DMHC} = [(\text{PHM}/\text{MPK})/(\text{PHB}/\text{BPK})]-1$ (4.50)

Assuming that the characteristics of the missile threat to the aircrafts are the same (i.e., a property of the missile), it can be said that

$$\text{PHM} = \text{PHB}$$

Therefore, $\text{DMHC} = (\text{BPK}-\text{MPK})/\text{MPK}$ (4.51)

But delta lethality (DL) is defined as

$$\text{DL} = (\text{BPK}-\text{MPK})/\text{BPK} \quad (4.52)$$

from equations 4.51 and 4.52 it can be deduced that

$$\text{DMHC} = \text{DL}/(1-\text{DL}) \quad (4.53)$$

This relationship is depicted graphically in Figure 4.21. Figure 4.22 shows the nomograph, that is obtained by combining the graphs obtained for the attack, fighter and carrier defense roles. Figures 4.12 and 4.19 have been worked upon a little in this process. Figure 4.12, has been enhanced by the addition of a scale representing the delta acquisition cost on the horizontal axis. This helps in determining if the cost elasticity of targets destroyed per loss is greater than 1.0, in which case the survivability enhancement at the given cost is cost effective. In Figure 4.19 a scale for the kill loss ratio multiplier is added

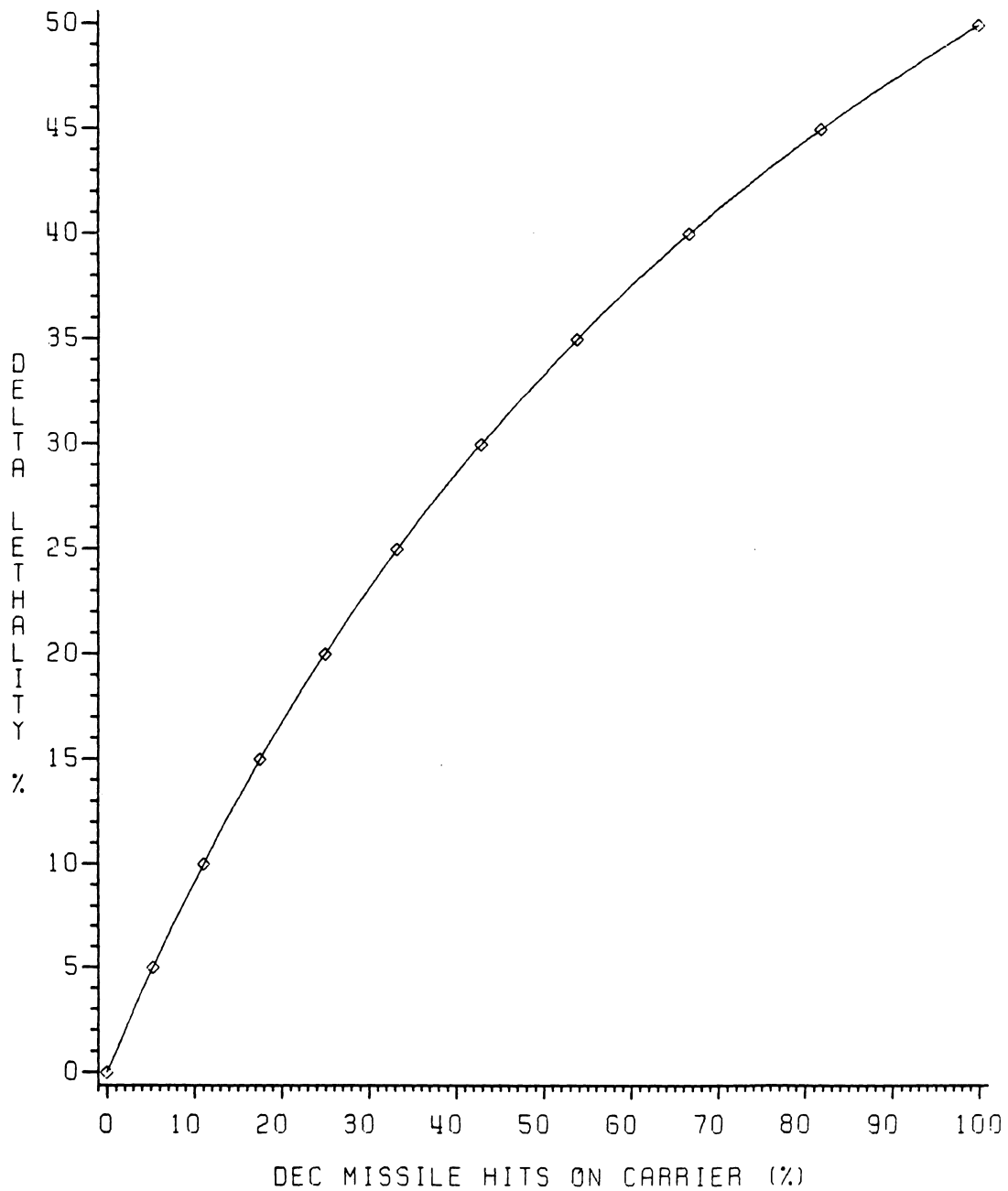


FIG 4.21 CARRIER DEFENSE : DL VS DMHC

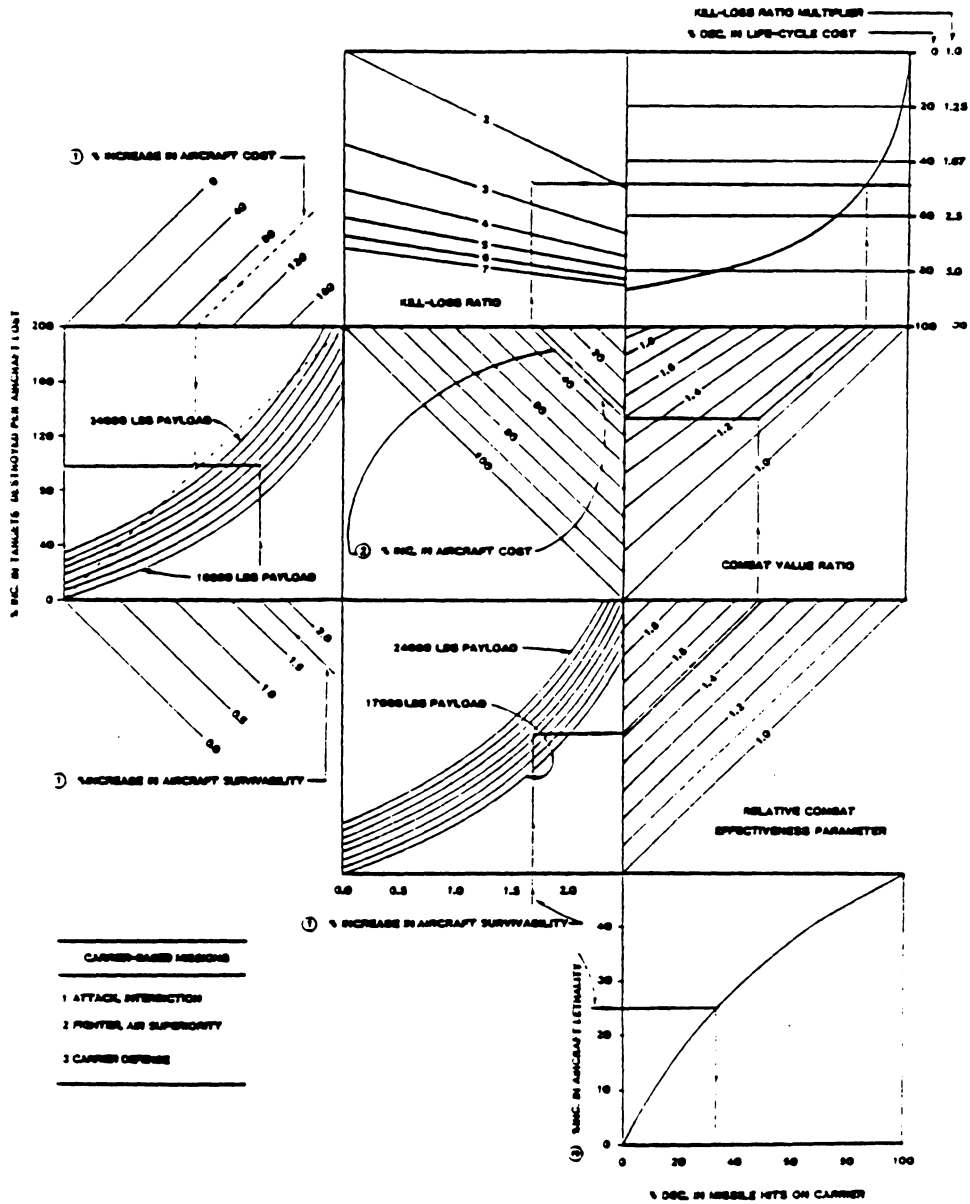


ILLUSTRATION OF SURVIVABILITY TRADEOFF ANALYSIS FOR 3 TYPES OF MISSIONS

Fig 4.22

| CARRIER-BASED MISSION | INPUTS | OUTPUTS |
|-----------------------|--|--|
| ATTACK/INTERDICTION | % INC. SURV. = 1.75% % INC. COST = 93% MOD. PAYLOAD = 20500 | % INC. TARGETS DESTROYED PER A/C LOST = 96% COST ELASTICITY 96% / 93% = 1.03 |
| AIR SUPERIORITY | % INC. SURV./LETH. = 1.7% % INC. COST = 33% MOD. PAYLOAD = 20500 | COMBAT VALUE RATIO = 1.13 % DEC. LIFE CYCLE COST = 47% KILL-LOSS RATIO = 2.5 |
| CARRIER DEFENSE | % INC. LETHALITY = 25% | % DEC. MISSILE HITS ON CARRIER = 33% |

SUMMARY OF SURVIVABILITY TRADEOFF ANALYSIS

Fig 4.23

alongside the scale for DPLCC. The survivability tradeoff analysis performed in Sections 4.6 and 4.7 are summarized in Figure 4.23 and is also shown in Figure 4.22. For the carrier defense role the input, increase in aircraft lethality, has been taken as 25% and it results in a 33% decrease in missile hits on the carrier.

5.0 SUMMARY

5.1 THINKING BIG

The pyramids, the Great Wall of China, the Appian Way, the Trans-Siberian Railroad, the Panama Canal, the Manhattan Project, and the Apollo Program -- all these projects are big, very big. In trying to manage, finance and build them -- much more was required than just an extrapolation of smaller similar projects. The ability to see the whole picture, to actively promote and keep the project focus, and to keep all the different participating disciplines working together was needed.

Many future technologies which could fall under Civil Engineering (if the profession is up to the challenge) such as a tunnel under the English Channel, flow-reversal of rivers emptying into the Arctic, high speed ground or subterranean transcontinental transport, and iceberg-transport-to-arid-regions schemes, are stymied by an inability to synthesize the contributions of narrowly-oriented, non-communicating specialists. A succession of "new" fields have emerged over the years to respond to this challenge -- in the fifties it was called "operations research"; in the sixties "programming and budgeting", in the seventies "systems analysis", and in the eighties "macro-engineering". They have in common the desire to deal with the gigantic and complex and the reliance on large-scale computer models to guide program management.

This research is concerned with a 250 billion dollar macro-engineering program -- defining the requirements of U.S. tactical airpower over the

next 15 years -- and "SURMAN", the combat aircraft survivability management computer model developed to guide this macro-engineering program. The purpose of this thesis is to sharpen and to focus the ability of the SURMAN to perform its policy assisting function by encapsulating it, accomplished by (1) developing a personal computer version of the model so as to make it available to more computer installations and this accessible to more analysts, and (2) presenting information relating inputs and outputs graphically using curves derived from experimentally designed computer runs. Chapter 3 describes PC SURMAN developed in this research in response to (1) and Chapter 4 outlines the steps in the development of graphs for performing survivability tradeoff analysis in response to (2) above.

5.2 RESOURCE ALLOCATION

The U.S. Department of Defense budget for fiscal year is \$284.7 billion which is, coincidentally, almost exactly the size of the U.S. budget deficit for this year. This mandates sharp scrutiny about the rationale for such massive defense spending. Along with the size of the defense budget, are the questions about the allocation of resources within the defense budget raised by recent and projected balances between long-term investment and immediate military operations [35].

An inescapable problem for defense planners is the trade-off between near-term and long-term objectives. If it is believed that the Soviet threat will be greatest in the 1990's, emphasis is placed on investment spending at the expense of readiness today. If the danger is perceived

as near term, the fancy weapons can be forgotten and concentration placed on the things that can be done quickly; this mainly means heavy spending on Operations and Maintenance. Over the past three years the investment accounts in the budget (procurement and research and development, R&D) have risen twice as fast as the account associated with operations and maintenance, O&M. Moreover, these same trends are expected to continue for at least the next few years. The effects of this allocation strategy are to increase aircraft inventories, increase survivability and reduce aircraft availability. The implications of this allocation strategy is, because of the introduction of decidedly more complex weapons systems in which rates of malfunction and repair times for equipment will increase, the possibilities of low availability factors will be exacerbated. Moreover, because the services are undergoing rapid, comprehensive, and simultaneous modernization, massive obsolescence in the future is virtually ensured. By the turn of the century, another administration will have to sustain high defense budgets simply in order to operate, support, and modernize these aircraft or, if the rate of growth in defense spending is to be slowed, they will be forced to such drastic measures as reducing the readiness of its combat air forces or mothballing part of its inventory.

One of the objectives of this research in developing the PC SURMAN is to detail the essential survivability management parameters and their causal relationships through the life cycle of aircraft systems. Pursuant to this, the model strives to link decision parameters to impact variables or figures of merit. The three key decision parameters identified in this research are survivability, availability and inventory. Their

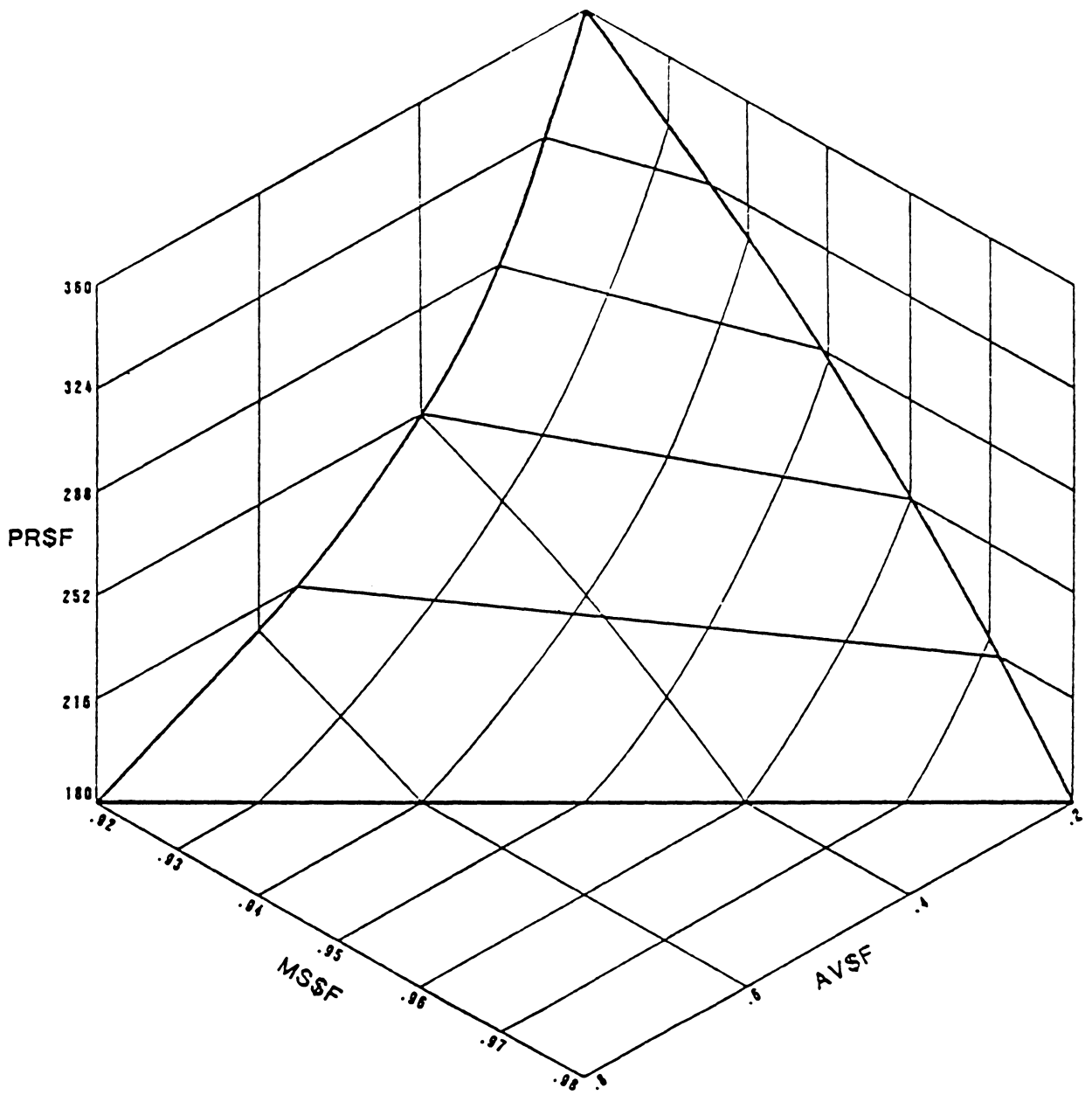
interrelationships, derived from the concepts developed in Chapter 3, can be displayed in the form of a surface such as in Figure 5.1.

In this figure $\$F$ refers to U.S. fighter aircraft and the two horizontal axes are the availability and mission survivability of the aircraft (AV $\$F$ and MS $\$F$). The vertical axis PR $\$F$ stands for procurement rate of $\$F$ which when integrated over time gives as aircraft inventory.

The ultimate technological assessment for combat aircraft is the level of attrition, or loss of mission capability under combat conditions. If attrition is higher than expected and mission objectives cannot be fulfilled due to misguided peacetime preparations, it is too late to do anything about it after war starts. The measures of mission effectiveness are varied so that any system can be evaluated with respect to its mission objectives. Some of the measures used in this trade-off analysis are "Life Cycle Cost per Surviving Aircraft" and "Kill-to-Loss Ratio". Basically, the problem can be stated as follows: allocate a given "Program Cost of Combat Aircraft" between procurement, operations and maintenance (O&M), and research, development, test and evaluation (RDT&E) so as to obtain the combination of aircraft inventory, aircraft availability, and aircraft survivability that will optimize the measure of effectiveness selected.

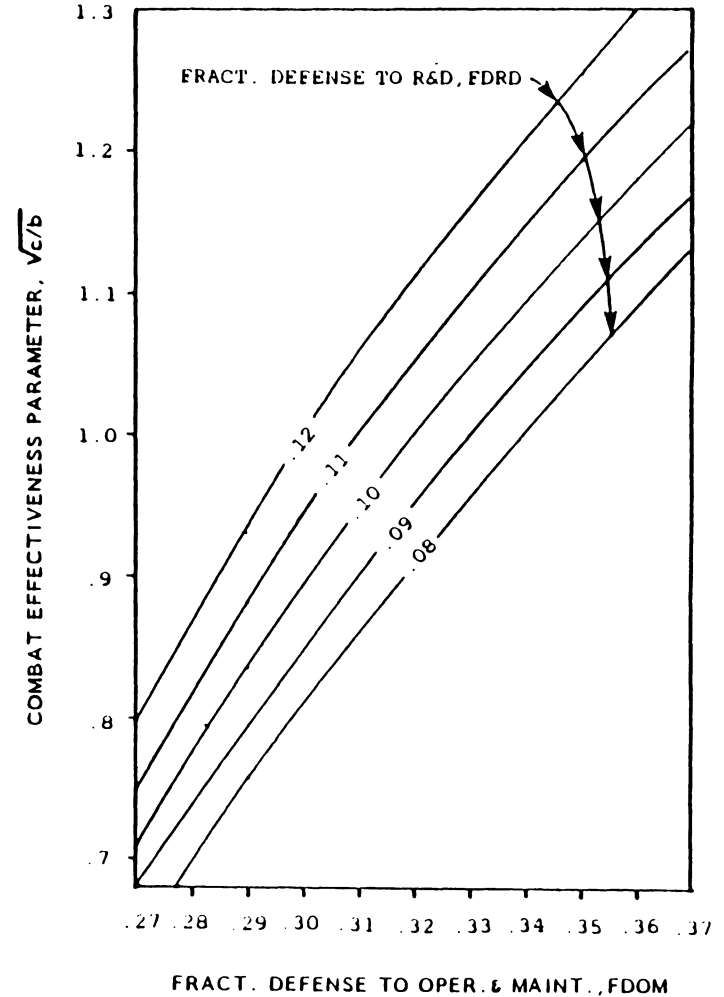
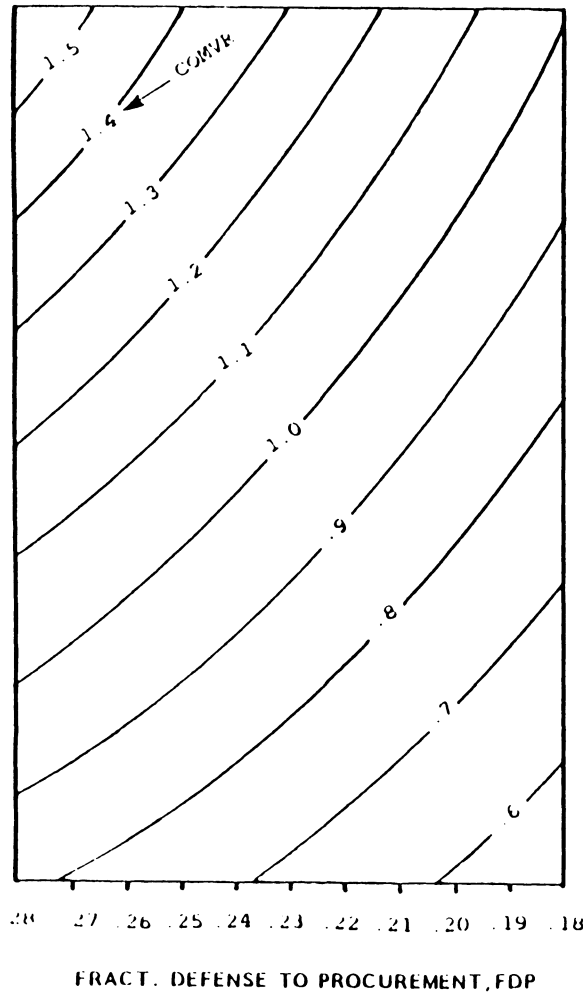
Figure 5.2 presents a summary of how budget allocation tradeoffs would be performed using PC SURMAN. The measure of effectiveness for evaluating the allocation between procurement, O&M, and RDT&E is the combat value ratio (COMVR).

The combat effectiveness parameter (CER) can be expressed as a function of the fraction of the defense spending to O&M (FDOM) and the



SURVIVABILITY, AVAILABILITY, INVENTORY TRADE-OFF SURFACE

FIG. 5.1



DEFENSE BUDGET TRADEOFF ANALYSIS CURVES
Fig 5.2

fraction of defense spending to RDT&E (FDRD). The relationship amongst the three has been discussed in the section on availability component of Chapter 3. This relationship has been expressed graphically as the loci of FDRD when relating CER and FDOM thus producing the family of curves on the half on the right side of Figure 5.2. COMVR is a function of the inventory and the effectiveness of the forces. The inventory in turn is a function of the defense spending to procurement. Thus COMVR can be expressed as a function of the fraction of defense spending to procurement (FDP) and CER. The interdependence of the three has been captured graphically as the loci of COMVR. The family of curves thus obtained makes up the half on the left side of Figure 5.2. The inputs to the resulting defense budget tradeoff analysis curves (Figure 5.2) are FDOM, FDRD and FDP and COMVR is obtained as the output. By varying the budget allocations between these three categories, differences in aircraft inventory, availability and survivability are obtained (see Surface in Figure 5.1).

5.3 SURVIVABILITY TRADEOFF ANALYSIS

Since World War II the unit cost of producing a first-line U.S. tactical combat aircraft has doubled, on the average, once every four years due to inflation, growing size and technical complexity of the aircraft themselves, and declining production rates. If the trend continues, in the year 2054, the entire defense budget will purchase just one tactical aircraft. Even if it is in Star Trek's Enterprise class, the United States will have achieved unilateral disarmament, ipso facto.

A persuasive decision dilemma has to do with the level of sophistication that should be built into weaponry. The services have a bias in favor of the most advanced technology, which they are invariably willing to wait for. The thinking is that U.S. technology is a comparative advantage that has to be kept in competing with the Soviet military threat. Survivability tradeoff analysis is one of the main tools used to make decisions on the implementation of survivability enhancement schemes that would seek to modernize the U.S. military power.

The results of the survivability tradeoff analysis of attack and fighter aircraft have been presented in Chapter 4. In this section the salient points of the same are touched upon.

The attack and fighter roles are each a special case of the general attrition model. The basis of the survivability tradeoff analysis of each case is that the aircrafts have specific missions and target objectives, which is a close approximation to the real world roles.

In the analysis of attack aircraft, a generic aircraft is attrited against a surface threat. To perform a tradeoff analysis, the survivability enhancements of the modified aircraft are incorporated through appropriate values of the deltas which are the input parameters. The measure of effectiveness that has been primarily used is the increase in target destroyed per loss, which when greater than 0 indicates that the modification makes the aircraft better. However it is felt that the cost elasticity of targets destroyed per loss (CETDPL) is a better indicator, for it takes into account the cost involved to obtain the improved performance also. The concept of using CETDPL is to better utilize the available resources to achieve superiority. The basic aim

is to achieve a design where the benefits (ITDPL) outweigh the cost (ICPA), i.e., when $CETDPL > 1.0$ and is maximum. Table 5.1 summarizes the results of the tradeoff analysis performed and illustrates the concept of CETDPL.

While Figure 4.12 can be used to determine ITDPL for various delta survivabilities, the portion of the nomograph (Figure 4.22) corresponding to the attack role can be used to obtain both ITDPL and CETDPL.

Referring to Table 5.1, even though ITD Δ L is greater than 0.0 in both the survivability enhancement schemes, it is seen that CETDPL is greater than 1.0 in Scheme 1 while it is less than 1.0 in Scheme 2. This implies that the survivability enhancement in Scheme 1 is more cost effective than Scheme 2. In fact for Scheme 1 the benefits outweigh the cost whilst it is the other way around for Scheme 2.

Therefore, Scheme 1 is a better survivability enhancement option.

Survivability tradeoff analysis for fighter aircraft has been performed and the results are presented in Chapter 4. In carrying out the tradeoff analysis, the modified aircraft is pitted against the baseline aircraft. The summary of the tradeoff analysis performed for two schemes of survivability enhancement is presented in Table 5.2. The measures of efficiency such as the combat effectiveness ratio, combat value ratio, decreased program life cycle cost, kill loss ratio multiplier and kill loss ratio are the outputs of the tradeoff analysis whose inputs are the deltas.

Referring to Table 5.2, all the measures of effectiveness of Scheme 1 are better than that of Scheme 2. So the modification Scheme 1 is

Table 5.1
 Summary of Survivability Tradeoff Analysis
 for Attack Aircraft

| Parameter | Baseline | Survivability Enhancement | |
|------------------|----------|---------------------------|----------|
| | Aircraft | Scheme 1 | Scheme 2 |
| MS\$ART | .960 | 0.9768 | 0.9744 |
| DSA | 0.0 | -0.0175 | -0.0150 |
| DAA | 0.0 | -0.9300 | -0.8000 |
| ICPA | 0.0 | 0.9300 | 0.8000 |
| BAN | | | |
| (\$AN=810) | 810 | 1563 | 1458 |
| PDT\$AL | | | |
| (PDTBAL=450,000) | 450,000 | 883,500 | 800,700 |
| ITD\$AL | 0.0 | 0.9634 | 0.7793 |
| CETBPL | 0.0 | 1.0360 | 0.9741 |

Table 5.2
 Summary of Survivability Tradeoff Analysis
 for Fighter Aircraft

| Parameter | Scheme 1 | Scheme 2 |
|-----------|----------|----------|
| BFN | 718 | 675 |
| DAF | -0.330 | -0.250 |
| SBF | 0.965 | 0.965 |
| DSF | -0.170 | -0.140 |
| SMF | .9814 | .9785 |
| CER | 1.507 | 1.401 |
| COMVR | 1.133 | 1.121 |
| DPLCC | .4692 | .4516 |
| KLR | 2.505 | 2.279 |

better; but it is to be borne in mind that there is also a greater spending warranted to achieve this.

Figures 4.17 to 4.20 can be used to obtain the measures of efficiency indicated in Table 5.3. The steps involved in using the nomograph (Figure 4.22) are illustrated for Scheme 1.

5.4 DISCUSSION

When planning to establish and maintain a comparative advantage of one force over an enemy threat, one of the considerations is the question regarding modification of baseline aircraft. The policies regarding the allocation of the defense budget to research and development, operations and maintenance, and procurement are influenced by the effectiveness of modifications to the baseline aircraft. It is therefore necessary to ascertain the results of possible modification. If the modified aircraft performs better than the baseline, it is desirable to modify the baseline aircraft. If modification is resorted to, then the mission survivability of the aircraft also changes and this has to be incorporated in the survivability tradeoff analysis. The performance of the modified and baseline aircraft are expressed in terms of the measures of effectiveness. Then based on the measures of effectiveness the decision regarding modification of the baseline aircrafts can be taken. This is of utmost importance in the peacetime buildup of the force.

In the PC SURMAN model, the analytical solution of the attrition component in the survivability submodel was used. In this case it was possible to obtain the analytical solution since the model was simple.

The analytical solution facilitated the computation of the measures of effectiveness at any point in time and then make a decision on the modification option. However, in models that are more complex it may not always be possible to obtain an analytical solution to help evaluate the modified aircraft. In such models, it is perceived that there would be some difficulty in the computation of the measures of effectiveness to help decide between the modified and baseline aircraft. It would probably require different solution intervals. Therefore it is necessary to devise a computational method using the capabilities of DYNAMO to solve this problem.

While the attrition submodel treats the survivabilities of \$\$ versus land, sea and air threat, the same has not been effectively used in the analytical solution to the attrition model. This particular aspect should be investigated and incorporated in the model.

In the tradeoff analysis for the fighter aircraft, the modified aircraft is attrited against the baseline aircraft. Thus the measures of effectiveness relate the performance of the modified aircraft to that of the baseline aircraft. In order to study the potential of alternative survivability enhancement scheme it would be necessary to first evaluate each scheme with respect to the baseline aircraft and then compare the results thus obtained. While the approach is rational, it is felt that an alternative approach comparing the performance of the aircraft versus a common threat would be a better basis. The results obtained by the former approach would indeed indicate which of the schemes is better, but it would not give the relative effectiveness of the schemes; whereas the later approach would give the relative effectiveness parameters. To

elucidate the point, the ratio of the measures of effectiveness of the alternative schemes in the first approach would indicate the better scheme, but it will not be the exact relative effectiveness of the schemes. Whereas in the latter scheme, a comparison of the measures of effectiveness would yield the relative effectiveness measure. A sister thesis [36] takes a step towards the second approach.

In this particular research, the survivability tradeoff analysis has been carried out for single mission aircraft. The curves and the nomographs developed have been developed on the basis of the single purpose mission. But with the advent of multimission aircraft, such as the proposed advanced tactical aircraft of the Navy, just around the corner, it would be a fruitful exercise to try to develop a similar methodology for the multimission aircrafts as an extension of this research.

5.5 FUTURE APPLICATIONS

Benefits of SURMAN and its derivatives developed in this research include: (1) forecasting of macro-behavior; (2) predicting consequences of government actions and failure to act; (3) conducting sensitivity analysis to establish research and data gathering priorities, and (4) providing aids to communication among specialists and in the achievement of understanding.

To meet the above requirements the computer simulation instrumentality must be comprehensive which means spanning the survivability phenomenon from design to operations. This means that while being R & D oriented

(the set of variables susceptible to direct influence by decision makers), it must be mission sensitive (the set of variables not under the direct control of decision makers but which must be influenced). SURMAN and its derivatives must incorporate variables and parameters that can describe the inherent capability of enemy threats, the effectiveness of those threats in particular environments, aircraft/air-vehicle damage susceptibility, the response of materials to threat impact, vulnerability reduction techniques, survivability enhancement trade-offs and figures of merit associated with aircraft design or usage alternatives.

In order to devise effective R&D investment strategies, we must thoroughly understand the broad operational effects resulting from survivability design. There must be a capability of optimizing the allocation of resources to modernization, improvement, and retrofit programs in full cognizance of the complex feedback interactions between survivability design, logistics requirements and mission operational objectives. A key aspect of future research is incorporating technological obsolescence into the survivability equation -- ascertaining aircraft innovations. Specifically, the next step in tying SURMAN to aircraft conceptual design evaluation (see Figure 4.1).

The effectiveness of a future weapon system depends in part on the successful co-ordination of the expertise in many different fields. A well-planned system will not only improve warfighting capability but can also reduce the life-cycle cost of the weapon. If one can critically challenge one's thinking vigorously in the early stage of the development of the system, expensive, and often less effective, modifications can be avoided in the future.

This project is a vehicle which can lead to improving capabilities in developing future combat aircraft by improving the method by which one can synthesize the various fields of expertise needed in the process. One of the payoffs will be the ability to avoid providing today's solutions as a basis for tomorrow's problems.

In striving to illuminate the issues and to define the problems of defense planning, in general, and aircraft combat survivability, in particular, we have ranged far and wide. Basically the problems and the issues are those of dynamic resource allocation -- "how much," "when," "where," "how," "what". How much sophistication should be built into combat aircraft to enhance survivability? When will the more critical Soviet threat occur -- in the near-term 1980's or the long term 1990's; where will it occur; and how can one maintain the greatest flexibility for the surest response? What sort of solution or plan can be expected from this research?

The answer to the last question subsumes the others and it is, "none"! There are no permanent solutions because either the problems change or the issues and value judgments are altered. There are already too many plans, most of which become irrelevant before they are produced in final form due to changing circumstances and time-consuming preparation. Therefore, no solution or plan is promised as the output of this research. Because solutions and plans are static responses to dynamic phenomena, we pledge only a dynamic planning, problem-solving instrumentality -- a policy-assisting model.

APPENDIX A. ANALYTICAL SOLUTION OF THE ATTRITION MODEL

The attrition model utilized in Chapters 3 and 4 is represented mathematically by the following system of differential equations

$$\frac{dM_t}{dt} = -r_1 M_t - bB_t \quad (\text{A-1})$$

$$\frac{dB_t}{dt} = -cM_t - r_2 B_t \quad (\text{A-2})$$

where the symbols are as explained earlier. In the state space form the same can be written as

$$\begin{matrix} \dot{M}_t \\ \dot{B}_t \end{matrix} = \begin{bmatrix} -r_1 & -b \\ -c & -r_2 \end{bmatrix} \begin{matrix} M_t \\ B_t \end{matrix} \quad (\text{A-3})$$

In vector notation,

$$\dot{\vec{X}} = \vec{A} \vec{X} \quad (\text{A-4})$$

where \vec{X} is the vector on the left hand side of equation A-3

\vec{A} is the matrix on the right hand side of equation A-3

and \vec{X} is the vector on the right hand side of equation A-3

Since the coefficients of the \bar{X} vector are constants, the problem is referred to as a constant coefficient problem. The standard solution to such a problem is

$$\bar{X} = e^{At} \bar{X}_0 \quad (A-5)$$

The Cayley-Hamilton Theorem [34] used to obtain e^{At} .

The characteristic equation of A is given by

$$\begin{vmatrix} \lambda+r_1 & b \\ c & \lambda+r_2 \end{vmatrix} = 0 \quad (A-6)$$

The characteristic polynomial in λ , $EP(\lambda)$, can thus be obtained from equation A-6 as

$$CP(\lambda) = \lambda^2 + (r_1+r_2)\lambda + r_1r_2 - bc = 0 \quad (A-7)$$

The roots of this equation are

$$\lambda_1 = \{-(r_1+r_2) + \sqrt{(r_1-r_2)^2 + 4bc}\} / 2 \quad (A-8)$$

$$\text{and } \lambda_2 = \{-(r_1+r_2) - \sqrt{(r_1-r_2)^2 + 4bc}\} / 2 \quad (A-9)$$

e^{λ} can be expressed in terms of the $CP(\lambda)$ as

$$e^{\lambda} = CP(\lambda)f(\lambda) + \text{remainder} \quad (A-10)$$

where $f(\lambda)$ is any function (to be assumed) and remainder is a term leftover after factorizing e^{λ} by $CP(\lambda)$ and $f(\lambda)$. Clearly the degree of the remainder has to be less than that of $CP(\lambda)$

$$\text{Let, remainder} = U + V\lambda \quad (A-11)$$

Substituting the values of λ_1 and λ_2 in equation A-10, and since $CP(\lambda_1) = CP(\lambda_2) = c$, we have

$$e^{\lambda_1 t} = U + V\lambda_1 \quad (\text{A-12})$$

$$\text{and } e^{\lambda_2 t} = U + V\lambda_2 \quad (\text{A-13})$$

Solving equation A-12 and A-13 simultaneously,

$$U = (\lambda_2 e^{\lambda_1 t} - \lambda_1 e^{\lambda_2 t}) / (\lambda_2 - \lambda_1) \quad (\text{A-14})$$

$$\text{and } V = (e^{\lambda_2 t} - e^{\lambda_1 t}) / (\lambda_2 - \lambda_1) \quad (\text{A-15})$$

Invoking the Cayley-Hamilton theorem, we can write

$$e^{\Lambda t} = UI + VA \quad (\text{A-16})$$

where I is the identity matrix.

Therefore,

$$e^{At} = \begin{vmatrix} -r_1 & -b \\ -c & -r_2 \end{vmatrix} * \frac{\begin{pmatrix} e^{\lambda_2 t} & -e^{\lambda_1 t} \\ \lambda_2 - \lambda_1 \end{pmatrix}}{\lambda_2 - \lambda_1} \quad (\text{A-17})$$

$$\left(\frac{\begin{pmatrix} \lambda_2 e^{\lambda_1 t} & -\lambda_1 e^{\lambda_2 t} \\ \lambda_2 - \lambda_1 \end{pmatrix}}{\lambda_2 - \lambda_1} \right) \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

Thus from equations A-5 and A-17 we obtain

$$M_t = \{ bB_0 (e^{\lambda_2 t} - e^{\lambda_1 t}) + M_0 [(r_1 + \lambda_1) e^{\lambda_2 t} - (r_1 + r_2) e^{\lambda_1 t}] \} / (\lambda_2 - \lambda_1) \quad (\text{A-18})$$

and

$$B_t = \{ -(M_0/b)(r_1 + \lambda_1)(r_1 + \lambda_2)(e^{\lambda_2 t} - e^{\lambda_1 t}) + B_0 [(r_1 + \lambda_1) e^{\lambda_1 t} - (r_1 + \lambda_2) e^{\lambda_2 t}] \} / (\lambda_2 - \lambda_1) \quad (\text{A-19})$$

Next, the time at which each force is depleted is obtained by equating equations A-18 and A-19 to zero and solving for t.

When $M_t = 0$,

$$-(bB_0/M_0)(e^{\lambda_2 t}) = (r_1 + \lambda_1)e^{\lambda_2 t} - (\lambda_1 + \lambda_2)e^{\lambda_1 t}$$

or

$$e^{\lambda_2 t} [r_1 + \lambda_1 + (bB_0/M_0)] = e^{\lambda_1 t} [r_1 + \lambda_2 + (bB_0/M_0)]$$

thus

$$t = \frac{1}{(\lambda_2 - \lambda_1)} \ln \left| \frac{[r_1 + \lambda_1 + (bB_0/M_0)]}{[r_1 + \lambda_2 + (bB_0/M_0)]} \right| \quad (\text{A-20})$$

Similarly when $B_t = 0$

$$(r_1 + \lambda_1)(r_1 + \lambda_2)(e^{\lambda_2 t} - e^{\lambda_1 t}) = (bB_0/M_0)[(r_1 + \lambda_1)e^{\lambda_1 t} - (r_1 + \lambda_2)e^{\lambda_2 t}]$$

$$\text{or } t = \frac{1}{(\lambda_2 - \lambda_1)} \ln \left| \frac{[(r_1 + \lambda_1)(r_2 + \lambda_2)(M_0/b) + B_0(r_1 + \lambda_2)]}{[(r_1 + \lambda_1)(r_1 + \lambda_2)(M_0/b) + B_0(r_1 + \lambda_1)]} \right| \quad (\text{A-21})$$

To obtain the summation of M_t and B_t we integrate equations A-18 and A-19 respectively.

$$\begin{aligned}
 \int_0^t M_t dt &= \frac{1}{\lambda_2 - \lambda_1} \int_0^t \{ bB_0 (e^{\lambda_2 t} - e^{\lambda_1 t}) + M_0 [(r_1 + \lambda_1) e^{\lambda_2 t} - (r_1 + \lambda_2) e^{\lambda_1 t}] \} dt \\
 \text{ie. } IM_t &= \frac{1}{(\lambda_2 - \lambda_1)} \left\{ bB_0 \left[\frac{(e^{\lambda_2 t} - 1)}{\lambda_2} - \frac{(e^{\lambda_1 t} - 1)}{\lambda_1} \right] \right. \\
 &\quad \left. + M_0 \left[\frac{(r_1 + \lambda_1)(e^{\lambda_2 t} - 1)}{\lambda_1} - \frac{(r_1 + \lambda_2)(e^{\lambda_1 t} - 1)}{\lambda_1} \right] \right\}
 \end{aligned} \tag{A-22}$$

and similarly;

$$\begin{aligned}
 \int_0^t B_t dt &= IB_t \\
 &= \frac{1}{(\lambda_2 - \lambda_1)} \left\{ \left(\frac{M_0}{b} \right) (r_1 + \lambda_1)(r_2 + \lambda_2) \right. \\
 &\quad \left. \left[\frac{e^{\lambda_1 t} - 1}{\lambda_1} - \frac{e^{\lambda_2 t} - 1}{\lambda_2} \right] \right. \\
 &\quad \left. + B_0 \left[\frac{(r_1 + \lambda_1)}{\lambda_1} (e^{\lambda_1 t} - 1) \right. \right. \\
 &\quad \left. \left. - \frac{(r_1 + \lambda_2)}{\lambda_2} (e^{\lambda_2 t} - 1) \right] \right\}
 \end{aligned} \tag{A-23}$$

Now the differential equations (A-1) and (A-2) lead us to the expressions for cumulative losses as

$$JM = bJB_t + r_1 JM_t$$

$$CLM = JM_{lost} = [SRB*AB*(1-SMA)*IB] + [SRM*AM*(1-SMS)*SM] \quad (A-24)$$

and

$$CLB = JB_{lost} = [SRM*AM*(1-SBA)*IM] + [SRB*AB*(1-SBS)*IB] \quad (A-25)$$

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