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MEMORANDUM REPORT BRL-MR-3815

BRL

HIGH-RESOLUTION, ITEM-LEVEL WEAPONS MODELING

PAUL H. DEITZ

MARCH 1990

U.S. ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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b. BRL Memorandum Report No. 3815, "High-Resolution, Item-Level Weapons Modeling," March 1990.

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High-Resolution, Item-Level Weapons Modeling†

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ABSTRACT

Modern item-level weapons analyses call for a computer environment which supports both geometric modeling and a substantial suite of predictive codes. This paper reviews the generation and interrogation of solid geometric models as well a diverse set of performance-related applications codes. Examples of geometric modeling of armored fighting vehicles are given; in addition, various applications codes including vulnerability, signature (optical/IR/MMW), neutron transport, and structural analysis are illustrated. Such modeling and analytical methods are critical for 1] evaluating the benefits and burdens of design options, 2] supplying necessary Measures-of-Performance for battlefield modeling, and 3] supporting and complementing the field testing of weapons systems.

1. INTRODUCTION TO ITEM-LEVEL MODELING

Item-level weapons modeling involves the study of a single military system such as a tank, aircraft or communications shelter The objective of such a study normally involves estimating one or more aspects of item performance in terms of its ability to meet a set of requirements. Typically a military system may fulfill multiple performance requirements so an item may be examined from many aspects What are typical examples of item-level analysis? They include estimates of weight, size, ability to withstand enemy fire (vulnerability), mobility, detectability (across many wave-length bands), and ability to inflict damage on a particular target class (lethality).

Item-level modeling and assessment are critical to the DoD for a number of reasons. This is the first level of assessment in which a technology can be properly evaluated in terms of actual benefits. For example, a new material for applique armor may appear promising in off-line tests. However only when this armor is applied to a vehicle with due consideration to actual placement and mounting constraints and further subjected to the various threats and attack directions, does a reliable picture emerge as to its true utility Another example might be the development of a radar coating for the suppression of armored fighting vehicle signatures A candidate material might show high absorptivity in laboratory tests, however, only when the practical constraints of applying such a material to the exterior of a vehicle (maintaining access for personnel, weapons, sights, etc.) can the utility of the approach be assessed. So item-level weapons modeling is the first instance where many technologies join with system design and the compromises and tradeoffs become identifiable and quantifiable.

Second, the results of item-level modeling form the basic building blocks from which larger integral assessments are performed. For example, all battlefield modeling whether at the battalion, division, or higher levels is built on probability of kill (PK) assessments of various firer/target matrices The data for these matrices are all the result of item-level modeling.

Third, item-level modeling supports and extends the utility of actual weapons testing. As is well known, many required field tests are extremely expensive. Item-level modeling assists in weapons assessment by extending the utility of test data for conditions and environments for which tests can't be performed due to constraints of time, costs, or materiel availability.

1.1 How is it Performed?

Item-level modeling can be divided into a two-step process The first is a Computer-Aided Design (CAD) phase in which a geometric description of the item is

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assembled The result of this is a mathematical file which represents the fully described shapes and materials of which the item is composed Phase two involves linking the geometric description to an application code to gain understanding about the nature or potential behavior of the item.

The BRL first embarked on this analysis tack some twenty years ago to gain insight into two specific forms of weapons performance: survivability/lethality and neutron transport. Whether a particular anti-tank munition will perforate a tank armor is inextricably related to both the characteristics of the munition as well as the system under attack. This includes the details of hit point, armor fall-back angle, line-of-sight projection, material properties, etc. So too the propagation of neutrons from a nuclear event through free space and potentially to occupants of an armored fighting vehicle is a phenomenon driven by the basic physics as applied to the specific geometric and material configuration encountered.

In the remainder of this section, various aspects of the generation of geometry will be discussed. Following sections will review specific applications

1.2 Early Geometric Modeling

In the years following World War II, when the discipline of vulnerability analysis first developed, analysts utilized blue-prints to project bullets through targets. Shotlines were traced manually through a tank or aircraft to catalogue lists of engaged components. Extracted by hand, as well, were points of intersection, surface normals, thicknesses, and materials, clearly a time-consuming process.

Late in the 1960's, the shotline interrogation process was automated to support the first item-level analysis, that of TOW warhead optimization against a tank To accomplish the first of the two-phase process noted above, a so-called target description was assembled of the target vehicle To do this, a method of target description preparation called *solid geometric modeling* was developed in which target geometry is described by a family of closed three-dimensional shapes such as cubes, spheres, cones, and the like. The resulting computer input file consisted of the required shapes and defining materials. Upon completion of this input preparation phase, a computer program was invoked which projected rays (or shotlines) through the target description to extract automatically what had formerly been an entirely manual task.

At this point it was possible to compute literally thousands of shotlines on computers which, by today's standards, were modest machines. The bottleneck of building, modifying, and validating target descriptions soon emerged as a substantial problem. Through the 1970's, that process was accomplished entirely by hand, with nothing remotely approximating today's world of interactive graphics. During the initial design process of the XM1 Tank, for example, none of the automated raycasting analyses could be invoked because it was not possible to model geometrically the competitive designs by hand in a timely fashion.

Early in the 1980's, the BRL made a study of the requirements for a suite of CAD tools necessary to support vulnerability and other kinds of item-level modeling. An in-depth review was performed of possible commercial candidates, at the time, none was found capable. An in-house development program was begun which has resulted in an extensive set of CAD programs which are now called BRL-CAD Although several commercial products in the area of solid geometric modeling have appeared in the market place, none has equaled the Army-developed package in its ability to support the demands of high-resolution item-level weapons modeling.

1.3 BRL-CAD Software Tools

BRL-CAD is an extensive suite of Army-generated, supported and owned software specifically designed for the geometric modeling of weapons systems. Consisting of some 200,000 lines of source code and approximately 70 individual programs, the heart of the CAD package is a geometric editor called MGED (for Multiple-device Graphics EDitor). This program, when executed on a suitable computer or engineering workstation, provides the visual feedback and operator control necessary to build, modify, and validate highly complex geometric models of tanks, aircraft, communications vans, etc.

There are many possible mathematical approaches to describing three-dimensional geometry This is why different modeling schemes are generally incompatible with one another Originally MGED provided for viewing and editing only the basic shapes mentioned earlier which were part of the first modeling scheme developed in the 1960's. However the BRL-CAD database has been designed to be extensible to new data representations. The database now supports the modeling representations used by Denver Research Institute, a key provider of geometry for the USAF, and a powerful, so-called, spline entity. This latter mathematical form is capable of following complex surface shapes such as those found in cast turrets and aircraft surfaces which are not amenable to modeling via simpler shapes.

Another significant set of tools in BRL-CAD supports raycasting In addition to supporting vulnerability/lethality analyses, raycasting is also used to simulate neutron trajectories and blast waves, calculate moments-of-inertia, and compute radar cross sections. These utilities are arranged to operate in parallel so as to take maximum advantage of modern computer architectures with multiple-processors (e.g. Cray, Alliant, Convex etc.).

A third set of BRL-CAD utilities supports the generation of images via what are called lighting models These models simulate what the eye would see from various positions in space Of note is the fact that there are many other utilities available for manipulating images, performing comparisons, creating labels, etc

1.4 Examples of Geometry

Over the past five years as the new CAD tools have been placed into production at BRL and other sites, many scores of target descriptions have been created. Illustrative of the high-resolution end of the modeling spectrum are the images shown in Figures 1 to 3. A high-detail version of the Bradley fighting vehicle is shown from the vehicle front-left (Figure 1) and rear-left (Figure 2). The target description used for these images was originally created to support standard vulnerability modeling during the Bradley development cycle. In 1985, the level of internal detail was increased to support the requirements of the Live-Fire testing program. The high level of exterior detail (tracks, hinges, handles) was added later to support high-frequency signature calculations in both the optical and radar bands.

A BRL-CAD lighting model was used to make these images. The model supports multiple sources of light; shadows beneath the main gun can be seen in Figure 1 due to two overhead sources. The amount of specular (shiny) or diffuse (rough-surface) reflections can be adjusted to simulate virtually any material, covering, or illumination condition (including stereo-image pairs).

An option exists within the lighting model to assign optical transparency to specific parts. Figure 3 illustrates this option in which the armor has been made nearly 100% transparent. This makes viewing of the internal components possible. Some reflection has been given to the armor so that it can be seen. Many other options are available including viewing only certain subsets of geometry and supporting animation for motion studies.

1.5 Other CAD Issues

There are many ramifications to the development and exploitation of this technology:

- Level of Detail: These CAD tools were originally developed simply to generate target descriptions more quickly. However as higher resolution geometry could be supported, many new and important applications have been developed.
- Portability The BRL-CAD package now operates over a dozen computer architectures spanning the range from $10K single-user workstations to $20M supercomputers. The ability to retarget code to new machines quickly has made it possible to exploit more fully the growing wealth of DoD computing resources and at the same time avoid "vendor lock in" to a narrow or cost-ineffective hardware base.
- Extensibility. Since the software is "owned" by the government, source code is available to all users Required extensions and modifications can be made by users of the code. New applications typically require new features or extensions.
- Applications Codes: There is a large body of applications codes which are linked to the BRL-CAD environment. Following sections will review some of the more prominent ones.
- Distribution: To date over 450 computer sites, Government, academia, and industry, have requested and been sent full source code. As new applications have been found and limits tested, feedback from users has contributed to enhanced releases.
- Sharing of Geometry: Even under the best of conditions, the generation of complex target descriptions is an expensive investment. However as workers share geometry, an economy-of-scale develops. Some analyses have been made possible because the geometry has been available when a specific need has arisen. In addition, since the BRL-CAD package is now in use at a significant number of contractor sites, an option exists for the Army to require a compatible digital database with contract deliverables. This greatly reduces the time required to analyze, for example, concept systems and production improvements.
- Networking: The CAD package makes copious use of the same intermachine networking standards as used in the DARPA MILNET/ ARPANET. This means that multiple machines both within a single laboratory or literally across the country can exchange files, share databases, and even aggregate computing power for high-demand tasks.

2. VULNERABILITY/LETHALITY (V/L) OVERVIEW

The *vulnerability* of a combat system is an assessment of its susceptibility to damage given a specific encounter with a particular threat. Therefore the term *vulnerability* is associated with the ability of military systems to continue fighting subsequent to an interaction with a lethal mechanism delivered by an opposing force. By contrast, *lethality* is the effectiveness with which an attacking weapon can inflict damage on a particular target.

The assessment of vulnerability plays a key role in many Army studies including:

- Concept Tradeoffs
- Vulnerability Reduction & Lethality Optimization
- Inputs to War Games
- Cost & Operational Effectiveness Analyses (COEAs)
- Spare Parts Requirements for Repair of Battle Damage
- Logistics

Over many years the requirements for weapons life-cycle support in the area V/L have resulted in a set of estimation tools We give a listing in order of increasing complexity:

- Penetration Performance
- Lumped Parameter Probability of Kill Modeling
- Expected-Value Point Burst Modeling
- Spare Parts Estimation
- Stochastic Point-Burst Modeling

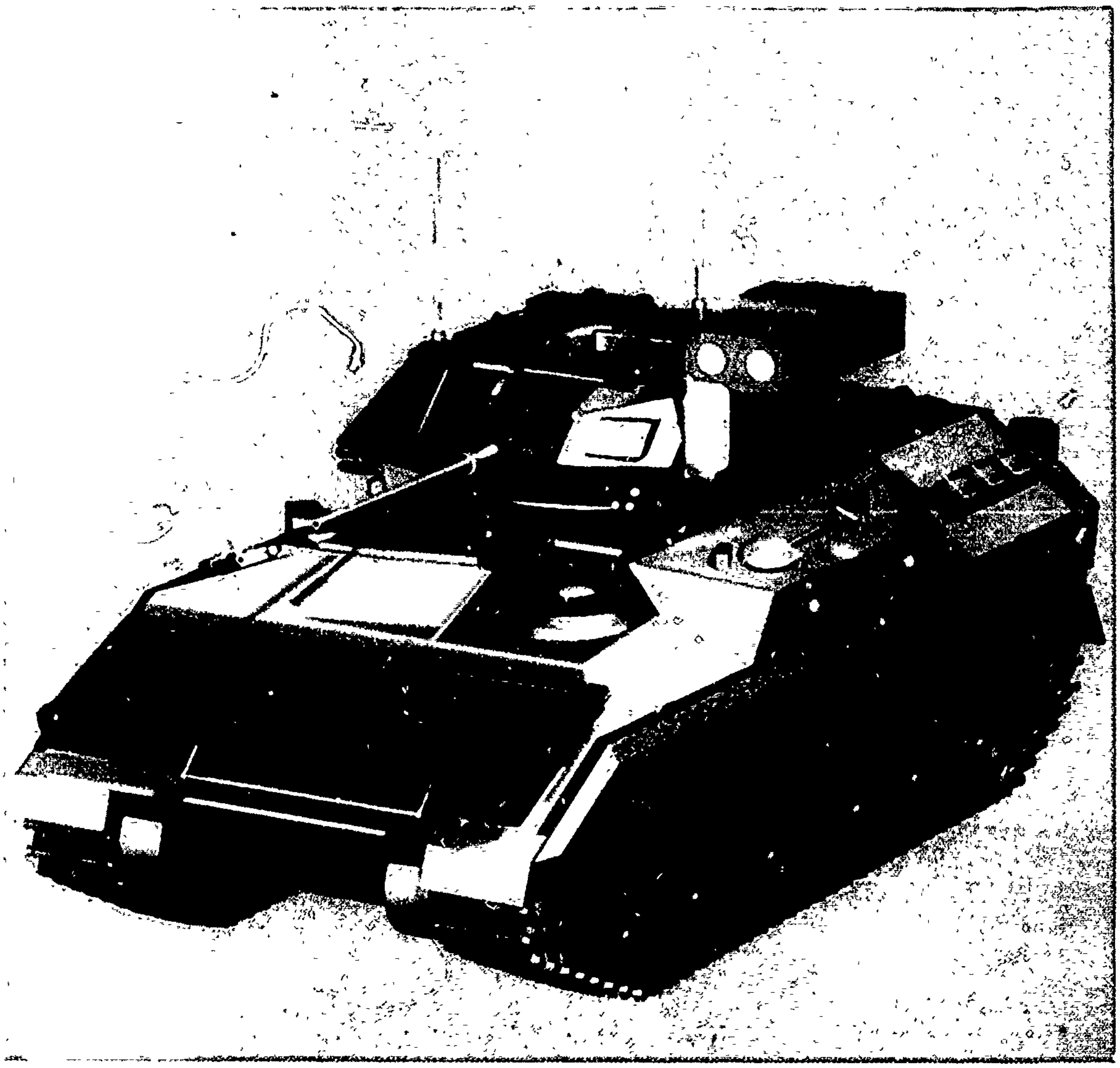


Figure 1. Frontal view of the Bradley Armored Fighting Vehicle built and viewed with the BRL-CAD package. The exterior geometry is highly detailed so as to support high-frequency radar and optical simulations. *(Geometric modeling by K. Applin, BRL.)*

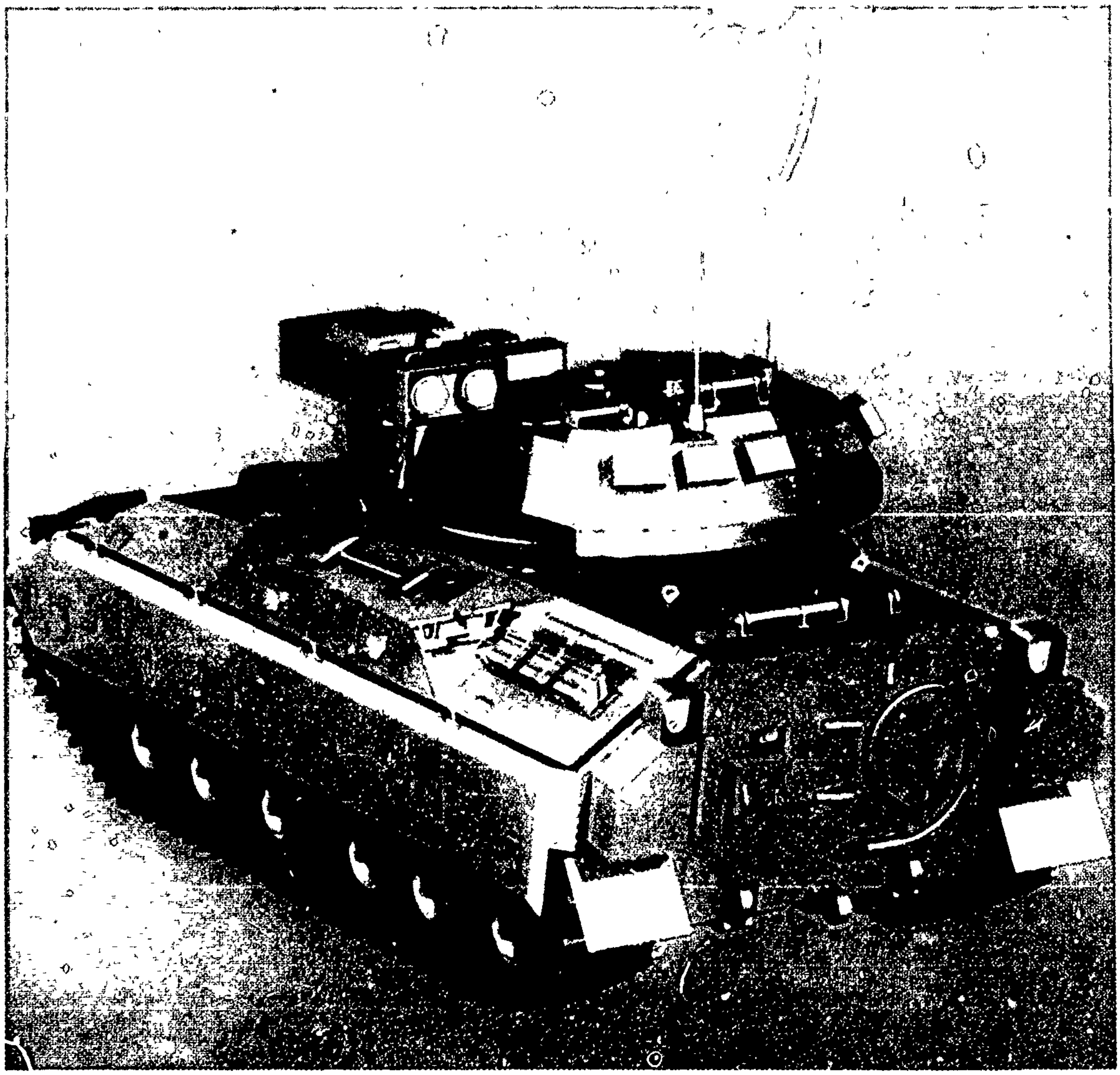


Figure 2. Rear view of the Bradley.

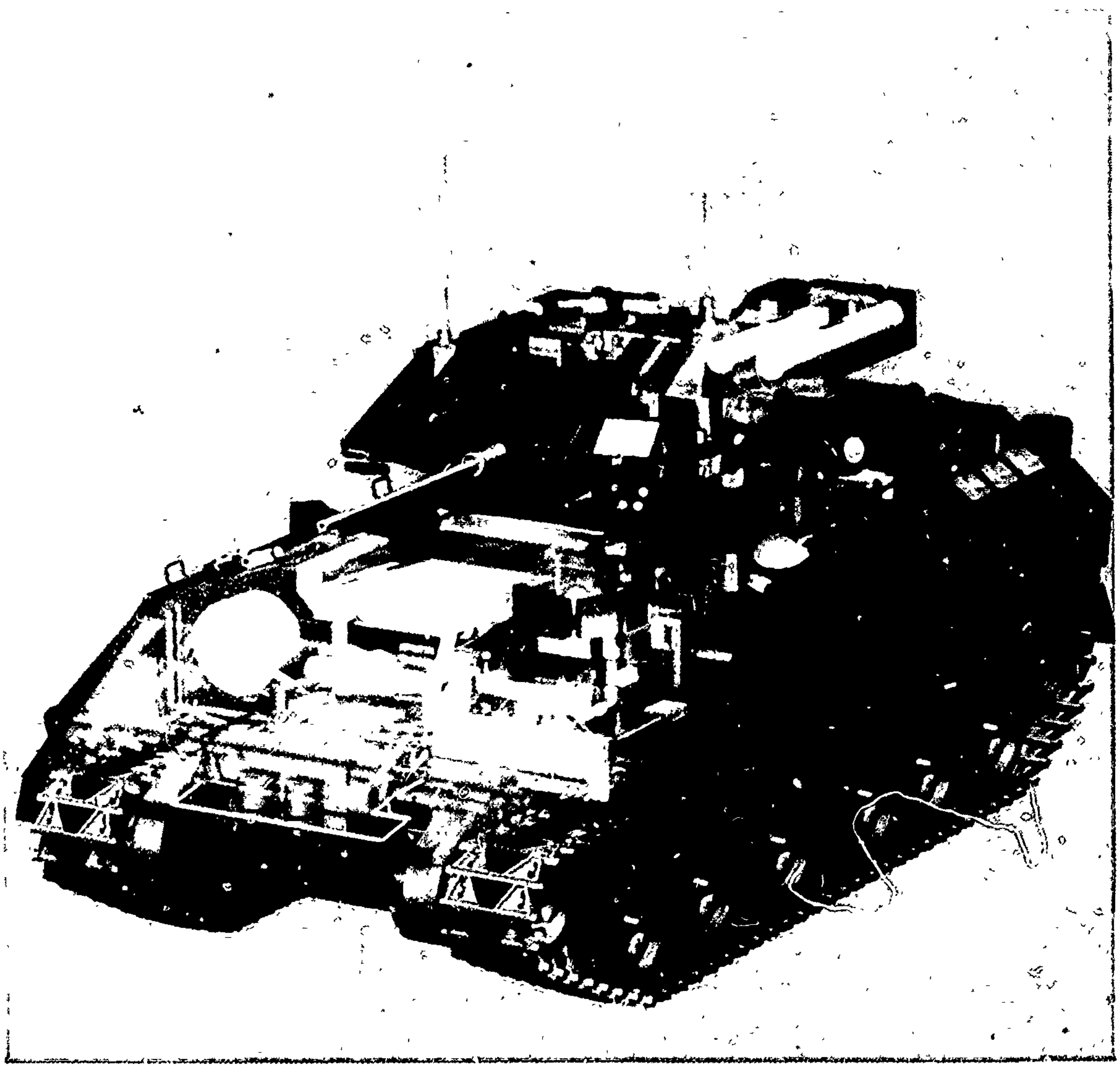


Figure 3. Transparent rendering of the Bradley Armored Fighting Vehicle. Using the same target description file as in Fig. 1, a lighting model option allows armor to be rendered transparent, revealing internal component placement.

2.1 Penetration Performance

Probably the most fundamental vulnerability question that can be raised about an Armored Fighting Vehicle (AFV) pertains to the protection from threat munitions afforded by its armor. The first figures of merit computed at the early concept phases of an AFV are usually protection levels for various threats vs. the ballistic hull and turret (BH&T). In order to accomplish this a number of inputs must be assembled. The threats must be specified, this task is the province of the Intelligence Community. The target geometry must be constructed using the CAD tools discussed in section **1.3**. Finally appropriate warhead/armor algorithms and data must be identified for the threats to be analyzed.

Figure 4 illustrates a concept target description generated for the Mobile Protected Gun System (MPGS) program a few years ago. Ignoring for the moment the exterior suspension system and interior components such as the crew, main gun, fuel, etc., this geometry is appropriately detailed to support penetration calculations. Table I illustrates the status of knowledge for various armor/threat pairings. In the case of some of the more advanced technology combinations, insufficient data exist and vulnerability analysts must make projections.

Once the target geometry and threat performance information is constructed, a BH&T study can proceed. Normally a four-inch grid is projected onto the target from a series of standard aspect angles A single shot-line is passed through each cell of the grid and the penetration performance calculated. Figure 5 illustrates a cell plot for an AFV for three horizontal attack azimuths. For the case of perforation, the cells can be color-coded according to the magnitude of residual penetration.

2.2 Framework for Vulnerability Assessment

The systematic study of AFV vulnerability originated during the 1950's when many firings of antitank rounds were performed against full-scale tanks. By 1960 over 1400 firings had been completed. A *catastrophic kill (K-Kill)* was defined as the total loss of the vehicle through explosion or burning. However it was observed that penetration into interior AFV space did not necessarily result in total vehicle loss As a result, new measures of effectiveness called probability of kills (or PKs) were developed for mobility and firepower functions. A *firepower kill* (F-Kill) results from an inability to deliver controlled fire within 10 minutes of being hit and the dysfunction is not repairable by the crew on the battlefield A *mobility kill* (M-Kill) results from an inability to execute controlled movement within 10 minutes of being hit and the dysfunction is not repairable by the crew on the battlefield.

The steps in the vulnerability logic process can be shown as:

1] Threat/Target Interaction →

2] Component Damage State(s) →

3] Loss of Automotive/Firepower Capabilities →

4] Probability of M-Kill/F-Kill

Step 1] *defines* a particular warhead/target combination After a shot, a set of damaged components may be encountered (Step 2]) If components or systems are killed which support mobility or firepower, there may be partial or total loss of these functions (evaluated in Step 3]). The reduction in these measures of performance (MoPs) is then related to a probability of M- or F-Kill (Step 4]). During the late 1950's, an armor board was convened to develop relationships between severity of AFV damage and M- and F-Kill values. The result of that study was the *Standard Damage Assessment List (SDAL);* it relates damage in Step 2] to PKs in Step 4] and in modified form is still in use today.

2.3 Lumped Parameter Modeling

The AFV tests of the 1950's together with the kill definitions and SDAL were used to develop the first ground vehicle vulnerability model. Called the *Compartment Code,* the model is built on the following data inputs.

- Simple geometry such as shown in Figure 4. The BH&T, exterior suspension, main gun, ammunition and fuel must be represented explicitly.
- Penetration relations for the warhead/armors under evaluation.
- Compartment damage correlation curves.

The correlation curves have been developed from field tests and, in effect, relate the warhead/armor interactions of Step 1] directly to PKs given in Step 4]. The Compartment Code methodology accounts explicitly for warhead penetration at the impact point. This process is used to estimate the probably of a K-Kill due to possible residual penetration interaction with ammunition or fuel. However the effects of all other damage mechanisms, including Behind-Armor Debris (BAD), are lumped into the correlation curves. These curves are then used to make the M- and F-Kill estimates. The model is efficient to run, and over many years the BRL and other organizations have used it as the principal AFV assessment tool. However, because of the way in which many complex damage mechanisms combine in a full-up field test, this model can only be used to predict shots for warhead/targets which have already been fired! Its extrapolatory capability to new vehicle configurations (e.g. spall liners, new armors) and/or new weapons is limited.

Although the outcome of any given ballistic event can be highly random, this model is built by averaging over many samples of field data. Thus lumped-parameter modeling yields an *average* (or first-moment) predictor of PK

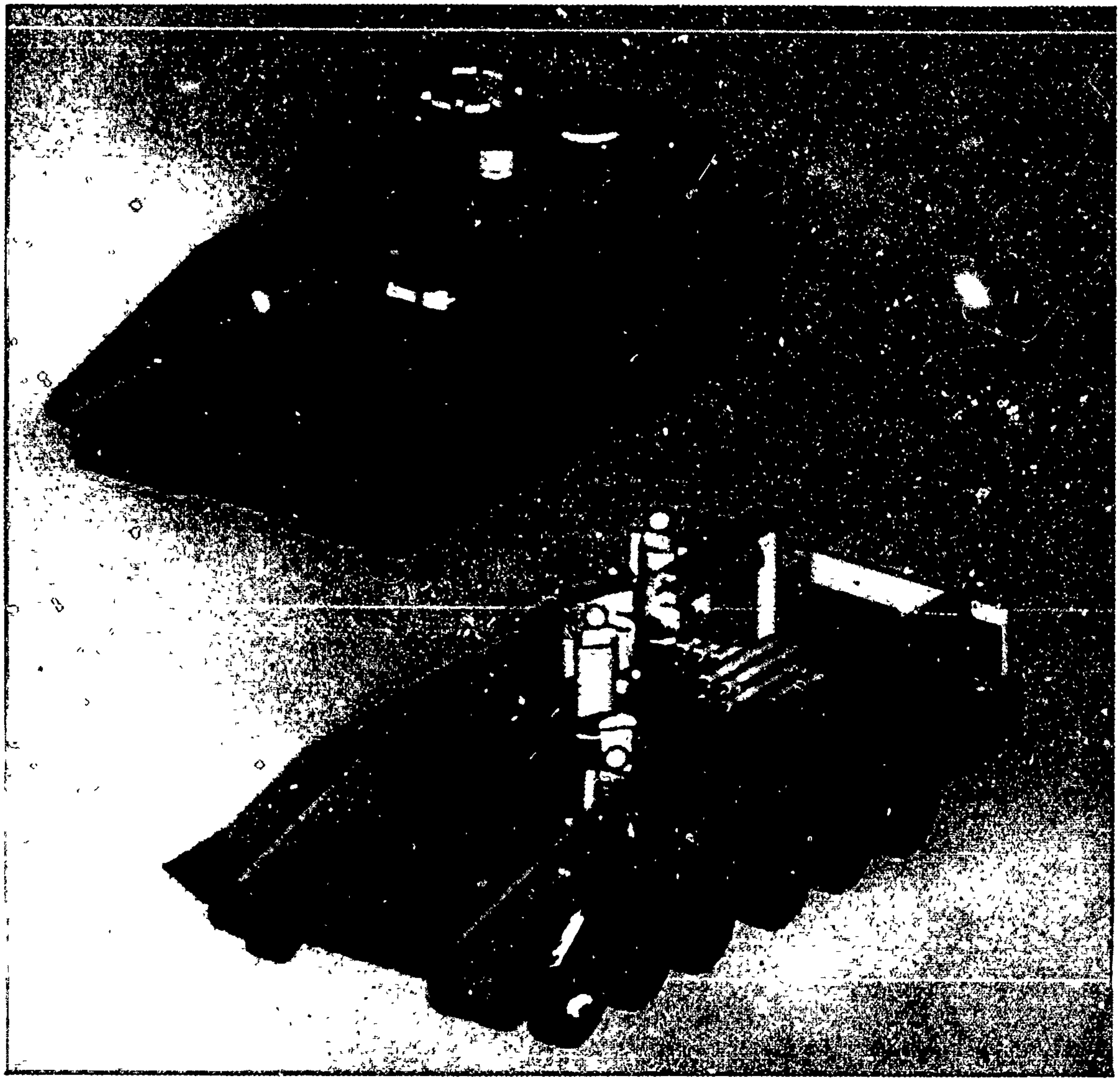


Figure 4. Concept design for a Mobile Protected Gun System (MPGS). Inspired by four prior TACOM designs, this BRL variant utilized a mix of rolled homogeneous armor (RHA), reactive, and ceramic armors. Although offering greater protection than the initial designs, the weight burden was increased by five tons. This level of geometric modeling is used to support penetration and lumped-parameter (e.g. Compartment Code) vulnerability analyses. *(Geometric model due to J. Anderson, BRL.)*

Table I. Status of Penetration Data. The matrix shows the status of penetration knowledge for each armor/warhead combination.

ARMOR TYPE	WARHEAD: Conventional Shaped Charge	Kinetic Energy Penetrators	Shaped Charge W/Crossing Vel	Tandem Shaped Charges	Explosively Formed Penetrators
Homogeneous Steel	3	3	2	2	3
Homogeneous Aluminum	3	3	2	2	3
Spaced Configurations of Steel or Aluminum	3	3	2	2	3
Laminates of Steel and Ceramics or Plastics	1	1	1	1	2
Single Element Reactives	2	2	2	2	2
Multiple Element Reactives	2	1	1	2	2
Reactive Appliques Over Steel/Ceramic Laminates	1	1	1	1	2
Special Armor	3	3	2	2	1

Legend:

1] No analytical penetration models exist. Critical data voids exists.

2] Rudimentary models exist. Additional data are required.

3] Extensive data available. Additional data are of some importance.

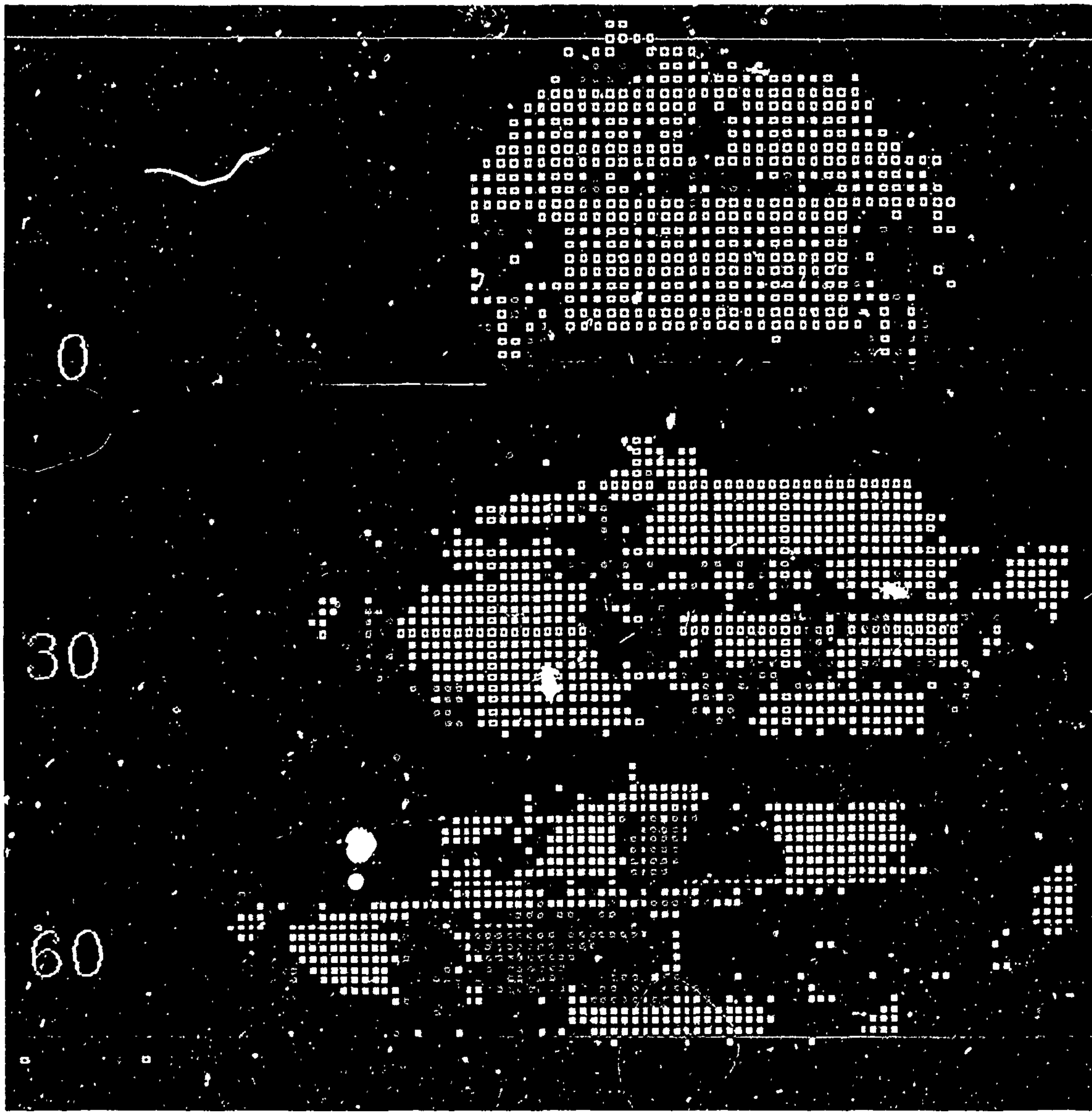


Figure 5. Standard cell plot used to display various estimates obtained from vulnerability analyses. Three views of a target are shown: 0, 30 and 60 degrees attack azimuth, 0 degrees elevation. From each of three views, a 4" x 4" grid is superimposed on the target geometry. A single shot is fired into each cell. For ground systems optional outputs include a] residual penetration, b] probability of catastrophic kill (P of K-Kill), c] probability of mobility kill (P of M-Kill), and d] probability of fire-power kill (P of F-Kill). *(Calculations by J. Ploskonka, BRL.)*

2.4 Expected-Value Point Burst Modeling

Because of the Compartment Code limitations, vulnerability analysts beginning in the 1970's sought a form of simulation which could be constructed from a series of ballistic submodels rather than built on data from full-up firings. This model would have the potential to evaluate AFVs significantly different from previously tested systems. The cost for this extensibility is the vital need for complete BAD and component-kill data bases.

Called *Expected-Value Point Burst* or in some cases *Component Models*, this class of simulation estimates explicitly both the effects of behind-armor warhead residual and debris.

To support Point-Burst vulnerability assessment, the following inputs must be assembled:

- A highly detailed target description. Every component (both critical and shielding) of the system must appear explicitly. If components are missing, they can't be assessed, and the final results may be biased towards a low estimate of vulnerability. Figure 6 illustrates the interior of an Abrams target description capable of supporting this level of assessment.
- As in simpler models, penetration relations are needed for all warhead/armor pairings that will be encountered; also for all components.
- BAD relations describing spall generation for all armor burst conditions as a function of penetration encounters.
- Component PK assessments for all vehicle critical components (those which support mobility or firepower functions). The form of the component PK characterization and the means used to describe the BAD must be compatible.
- A set of fault trees (or "wiring diagrams") which reflect the system function of all critical components. In the course of the computer simulation, if a given critical component is judged to have been killed, the accompanying fault tree shows whether residual mobility or firepower functions remain.

In the last decade a half-dozen variants on the Point-Burst model have been generated which differ only in the manner in which spall and component PKs are characterized. The status of BAD knowledge is given in Table II.

In addition to the detailed inputs, computer run time increases markedly, mainly due to the shot-line interrogation of the high-resolution target description needed to model the spall process. As in the case of the Compartment Model, the output of these models is an estimate of *expected* M and F PKs.

2.5 Spare Parts Estimation

During the past ten years, interest has grown in the areas of battle-field resupply and spare part stockpiling. The point-burst methodology described above was modified to account for two metrics. component damage sufficient to warrant replacement and required repair time. In effect the component PK metrics of the Point-Burst methodology were lowered to reflect a damage threshold rather than a kill condition.

The input detail and run constraints for Spare Parts Estimation are commensurate with Point-Burst methods.

2.6 Stochastic Point-Burst Modeling

In the last few years, many live-fire test programs have been initiated as a result of the National Defense Authorization Act for FY 1987. One of the earliest AFVs tested with overmatching munitions was the Bradley Fighting Vehicle. When the BRL was confronted with the requirement to predict each of some 150 shots before the actual firings it chose an existing (Expected-Value) Point-Burst Code. Since the Bradley had never been extensively tested with overmatching munitions exercising a version of the Compartment Model was not possible.

When the field-derived PKs were compared with the estimates from the model, certain variations were observed. Critics of vulnerability modeling rated the quality of predictions in terms of the percent variation with field value.

There were three substantial problems at the time in using the extant Point-Burst models in support of live-fire testing:

- Lack of Randomness: Some reflection on the complexity of the destructive processes of ballistic vulnerability soon leads one to the conclusion that there are many aspects of armor penetration, fracture, spall generation, and component dysfunction that could lead to significant shot-to-shot variability were it possible to repeat a given shot configuration many times. In practice the costs of testing and the availability of expensive materiel mean that precision repeated shots are a rarity.
- No Predicted Component Kill Combinations: The extant Point-Burst models predicted the probability of killing components *individually*, but not the probability of killing components by specific *groups*. And it is the latter which is the primary observable in Live-Fire testing.
- Improper Use of Statistics: Various critics of vulnerability modeling rated the quality of assessments by comparing directly the single field PKs with the (first-moment) predictions. This is the equivalent of comparing a single sample from a gaussian (bell curve) distribution with the average of the same curve, no useful inferences can be drawn.

At the onset of the Abrams Live-Fire program, a new stochastic point-burst code called SQuASH was developed. This is a Monte Carlo code which varies a] penetrator hit location over a small area, b] magnitude of warhead performance, c] deflection of residual penetrator, d] the statistics of spall generation, and e] the component PKs.

SQuASH was used to predict the 48 Abrams live-fire shots. Although the model predictions and field

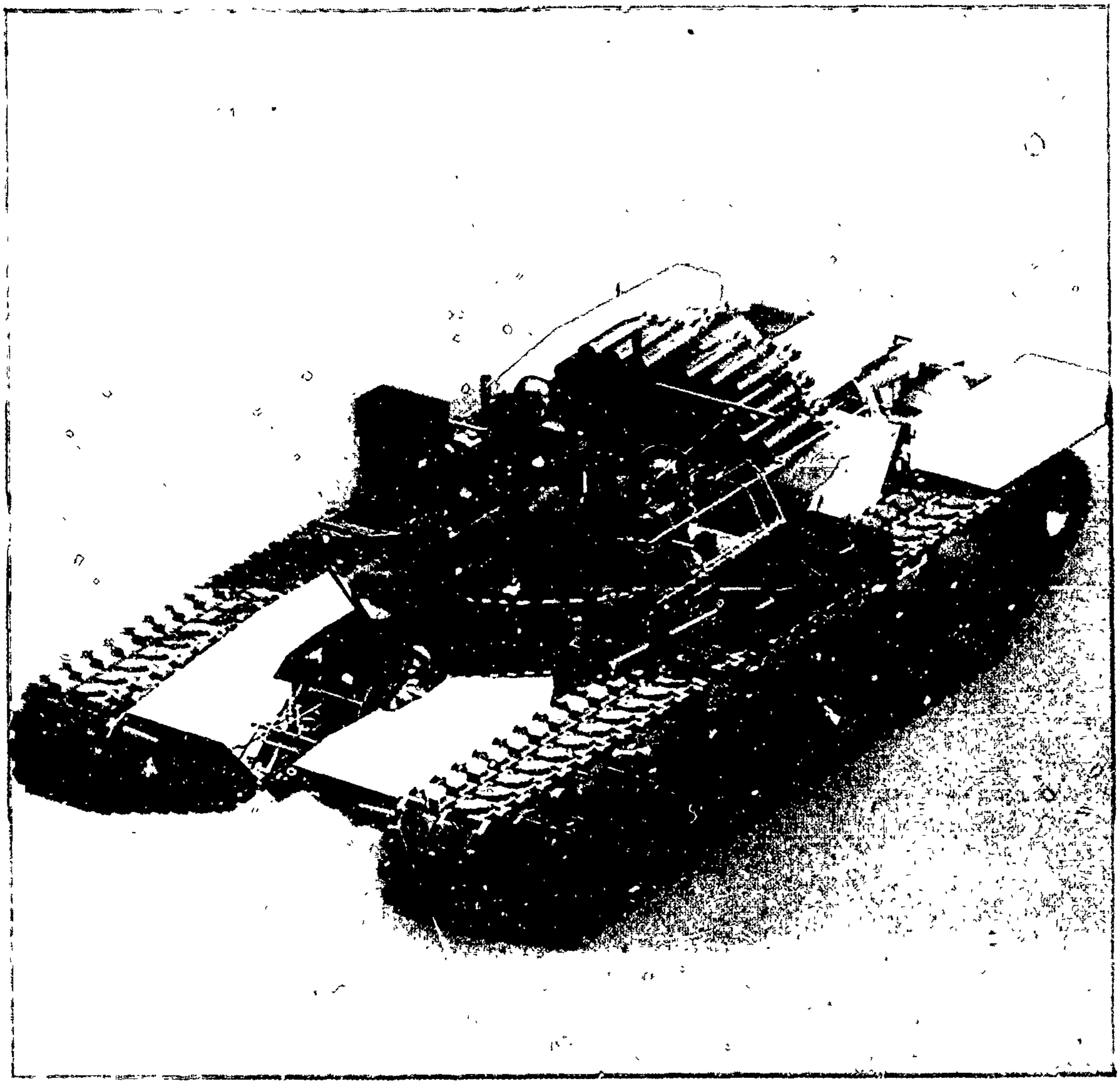


Figure 6. Front-left elevated view of the current Abrams target description with the armor and main armament stripped away. Generated to support high-resolution point-burst vulnerability analysis, this description is composed of some 5000 individual components including hydraulic lines and electrical wires. *(Geometric model due to C. Dively, S. Henry and J. Vanderbeek, BRL.)*

Table II. Status of Behind-Armor Debris (BAD) Data. The matrix shows the status of BAD knowledge for each armor/warhead combination.

	WARHEAD				
ARMOR TYPE	Conventional Shaped Charge	Kinetic Energy Penetrators	Shaped Charge W/Crossing Vel	Tandem Shaped Charges	Explosively Formed Penetrators
Homogeneous Steel	3	2	1	1	3
Homogeneous Aluminum	3	2	1	1	1
Spaced Configurations of Steel or Aluminum	2	1	1	1	2
Laminates of Steel and Ceramics or Plastics	1	1	1	1	1
Single Element Reactives	2	1	1	1	1
Multiple Element Reactives	1	1	1	1	1
Reactive Appliques Over Steel/Ceramic Laminates	1	1	1	1	1
Special Armor	2	2	1	1	1

Legend:

1] No analytical behind-armor debris models exist. Critical data void exists.

2] Rudimentary models exist. Additional data are required.

3] Extensive data available. Additional data are of some importance.

observations are still being analyzed, it is clear that an extraordinarily large number of variations in component damage can occur in live-fire testing. In one shot simulation more than 1.8 million distinct damage states were calculated as possible outcomes (Step 2], **2.2 Framework**). When these damage states were mapped via the SDAL to generate PK histograms, disperse and ill-behaved statistics were observed. In some cases 20% of the PKs were zero, another 20% were unity, and the rest were distributed between the extremes. Not atypically, the average PK (first-moment) occurs where not a single outcome is found!

Much more work, both analytical and experimental, will be required to provide precise uncertainty limits on this class of computation.

2.7 Summary of Vulnerability Methods

We have reviewed here a set of item-level vulnerability tools used mainly to evaluate AFVs for various direct-fire threats. Although the nature and relative importance of certain damage mechanisms are different, a similar set of codes can be found in the evaluation of air targets. In general as an item moves from concept towards development and beyond, the vulnerability assessments become more detailed and resource intensive. Table III gives time bounds (in man-months) required for the various models described above.

3. PREDICTIVE SIGNATURES

In this section, some techniques of predicting military signatures will be described. The methods used can be considered variations on the general approach to item-level modeling previously described.

3.1 Optical Lighting

In a previous section the BRL-lighting model was used to create simulated optical images of various military targets. With this lighting calculation, the amount of specular (shiny) or diffuse (rough-surface) reflections can be adjusted to simulate virtually any material, covering or illumination condition. Transparency, illustrated with glass armor, was also demonstrated.

The lighting model can also support a geometric configuration in which an optical beam is directed towards a target from one direction while viewing takes place from another This configuration is typical of laser-designator studies of the type needed to support the Copperhead laser-guided artillery projectile The Bradley vehicle description is used to illustrate this capability in Figure 7 The optical scattering pattern is distributed across the turret while the target outline is rendered in wire-frame mode so that its orientation can be inferred.

A second optical prediction result is shown in Figure 8. Here the Bradley target description is used to show the view from an overhead optical sensor as might be encountered in a smart-munitions simulation. The Bradley has been placed on a ground plane and an optical source simulating the sun positioned above Image 8a (upper left) shows a high-definition image, complete with ground shadow. To illustrate the processing methods used to simulate noise and resolution constraints, the image given in 8a was modified *via* an algorithm which introduces noise. The result is shown in Figure 8b (upper right) Next a sequence of two optical filtering operations was performed to reduce the image resolution The final result is shown in Figure 8c (lower left).

There are also methods to take a two-dimensional image (such as a camouflage pattern) and transfer it onto the surface of a target description. This procedure might be used to support optical pattern recognition studies

3.2 Infrared Modeling

Predictive signature modeling can be extended to other wavelength regions Figure 9 illustrates a simple procedure which shows how the utility of measurements can be extended greatly In the upper image, an infrared (IR) image is shown of an actual Soviet T62 tank. The temperatures inferred by measurement are made visible by false-color imaging. A calibration bar below the image gives the appropriate color-temperature associations To give greater utility to these measurements, a target description of a T62 has been configured identically to the measured vehicle to include the same gun-elevation angle. In a special mapping procedure, the measured temperatures (top) have been mapped (transferred) to the target geometry (below). Through this procedure, the target can be viewed from angles other than that of data capture; in addition, the target thermal performance can be extrapolated to other IR bands *via* standard algorithms of radiation physics.

Over the past few years the Keweenaw Research Center and TACOM have developed a predictive IR model. Work is currently in progress to replace many of the tedious manually prepared inputs with geometric and material data converted automatically from BRL-CAD target files.

3.3 Radar Modeling

The final examples of predictive signatures involve the calculated radar properties of military targets Historically radars were used to infer target range and closing rates. For the early radars, a figure of merit, the radar cross section, was of key importance, as it represents the efficiency with which radar waves are scattered back to the receiver. Certain modern radars, when placed on moving platforms such as aircraft, can be used to form a two-dimensional image of targets. Radar imagery of this class is called synthetic aperture radar (SAR) A description of an M48 tank has been analyzed with a SAR program (due to the Environmental Research Institute of Michigan), and the results are shown in Figures 10 and 11. In the upper right of Figure 10 the orientation of the target vehicle is shown as seen with respect to the radar. A horizontal flight path (left to right) is assumed The properties of SAR processing are such that following signal detection and manipulation an image is derived which resolves the

Table III. Models *vs.* Input requirements/preparation times (in months). All estimates assume the availability of a] Intelligence Community validated threat specification and b] detailed item configuration specification by the system advocate.

	RESOURCE						
	Target Description (*ab initio*)						
ANALYSIS TYPE	Total Man-Mths	Min El Time‡	Penetration Relations/ Data Bases*	BAD Relations/ Data Bases†	Component/ System Logic	Component PKs	Total El Time
Penetration Performance	3	1	0.5 - 1	0	0	0	4
Lumped Parameter PK	4	2	0.5 - 1	0	0	0	5
Exp Value Point Burst	16 - 18	9 - 12	0.5 - 1	3 - 6	4 - 6	6 - 12	11 - 14
Spare Parts	20 - 22	10 - 14	0.5 - 1	3 - 6	4 - 6	6 - 12	12 - 16
Stochastic Point-Burst	16 - 18	9 - 12	0.5 - 1	1 - 2	4 - 6	1 - 4	11 - 14

‡ With multiple analysts, total elapsed time can be compressed.

* Depends on availability of data. See Table I.

† Depends on availability of data. See Table II.

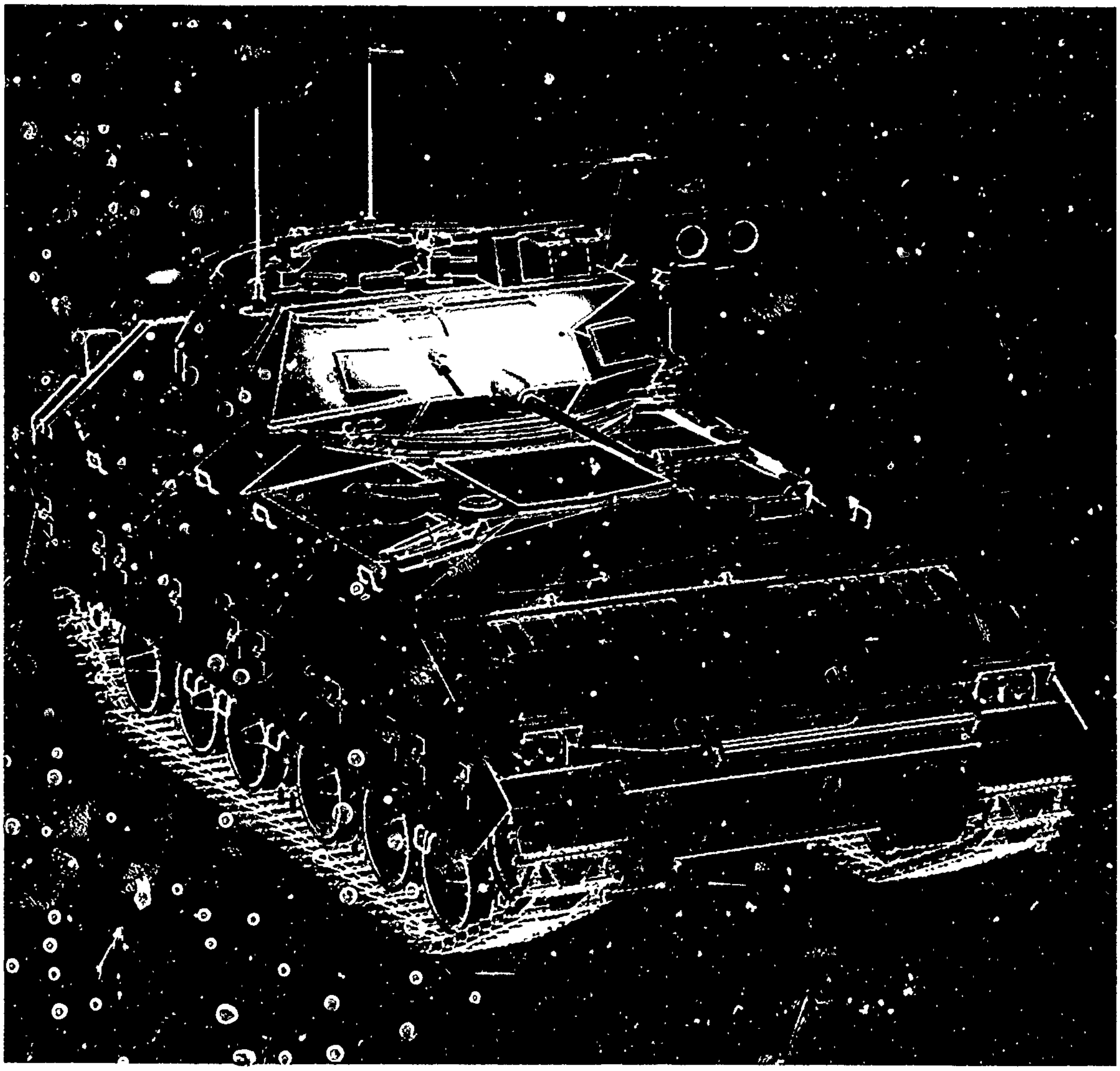


Figure 7. Simulation of a laser designator on the Bradley vehicle. Using the model, any target surface condition or illumination/viewer orientations can be used. *(Lighting model result due to G. Moss, BRL.)*

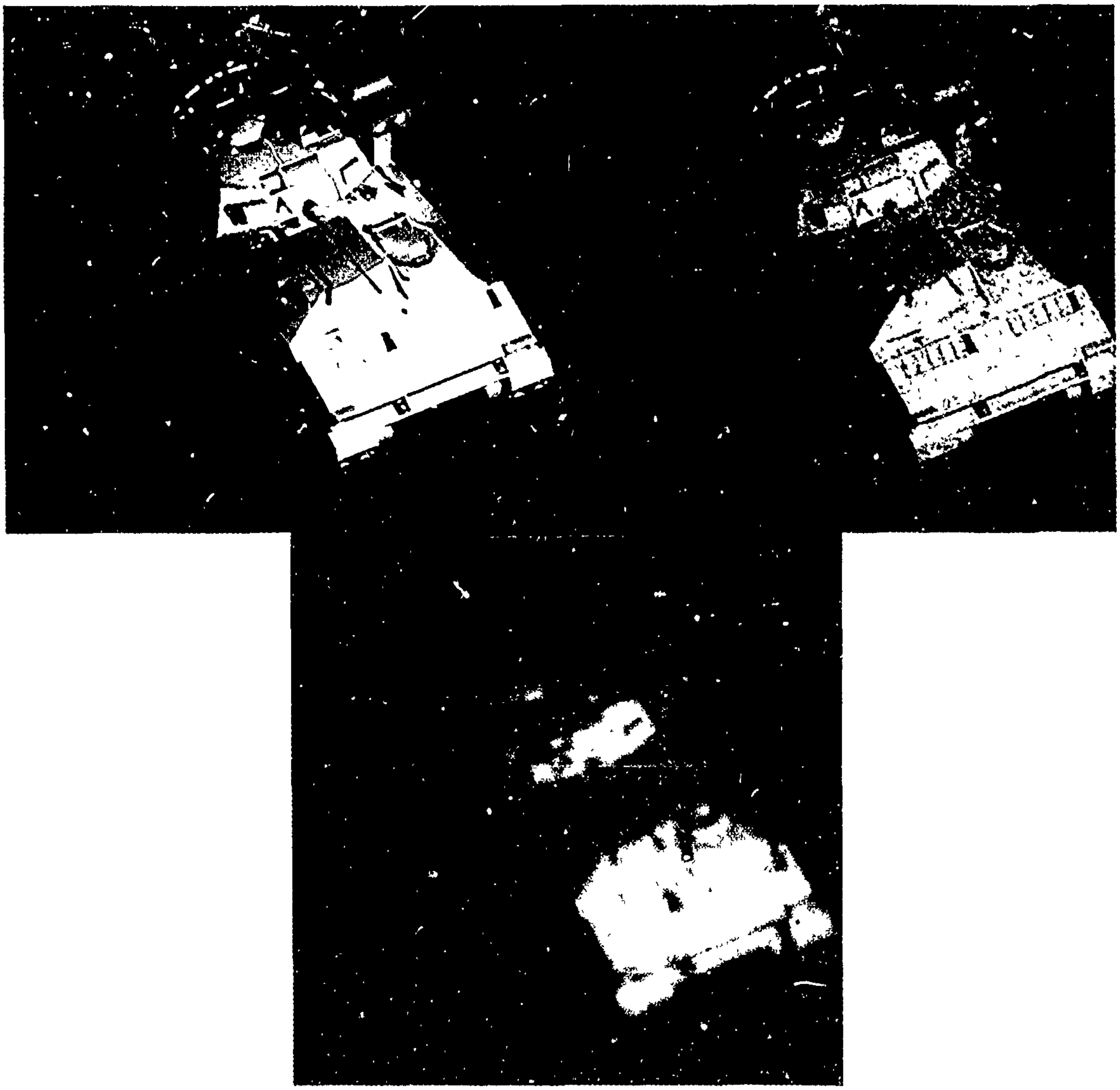


Figure 8. Simulation of an overhead smart-munition sensor. A ground plane has been placed under a Bradley vehicle with the sun positioned overhead (upper left). Noise has been mixed with the first image (upper right). In the lower left image, filtering operations have been performed to reduce the (simulated) resolving power of the sensor. *(Lighting model result due to G. Moss and E. Davisson, BRL.)*

Figure 9. Upper image shows IR field data of Soviet T62 tank. Lower image shows the field data mapped onto the surface of a target description. With this method, thermal images can be generated for other viewer positions and thermal regions. *(IR model result due to G. Moss, BRL.)*

Figure 10. Two images of an M48 tank which illustrate the synthetic aperture radar (SAR) process. In the upper-right is the target as viewed by the radar. Below is the image orientation after radar processing. *(Images due to E. Davisson, BRL.)*

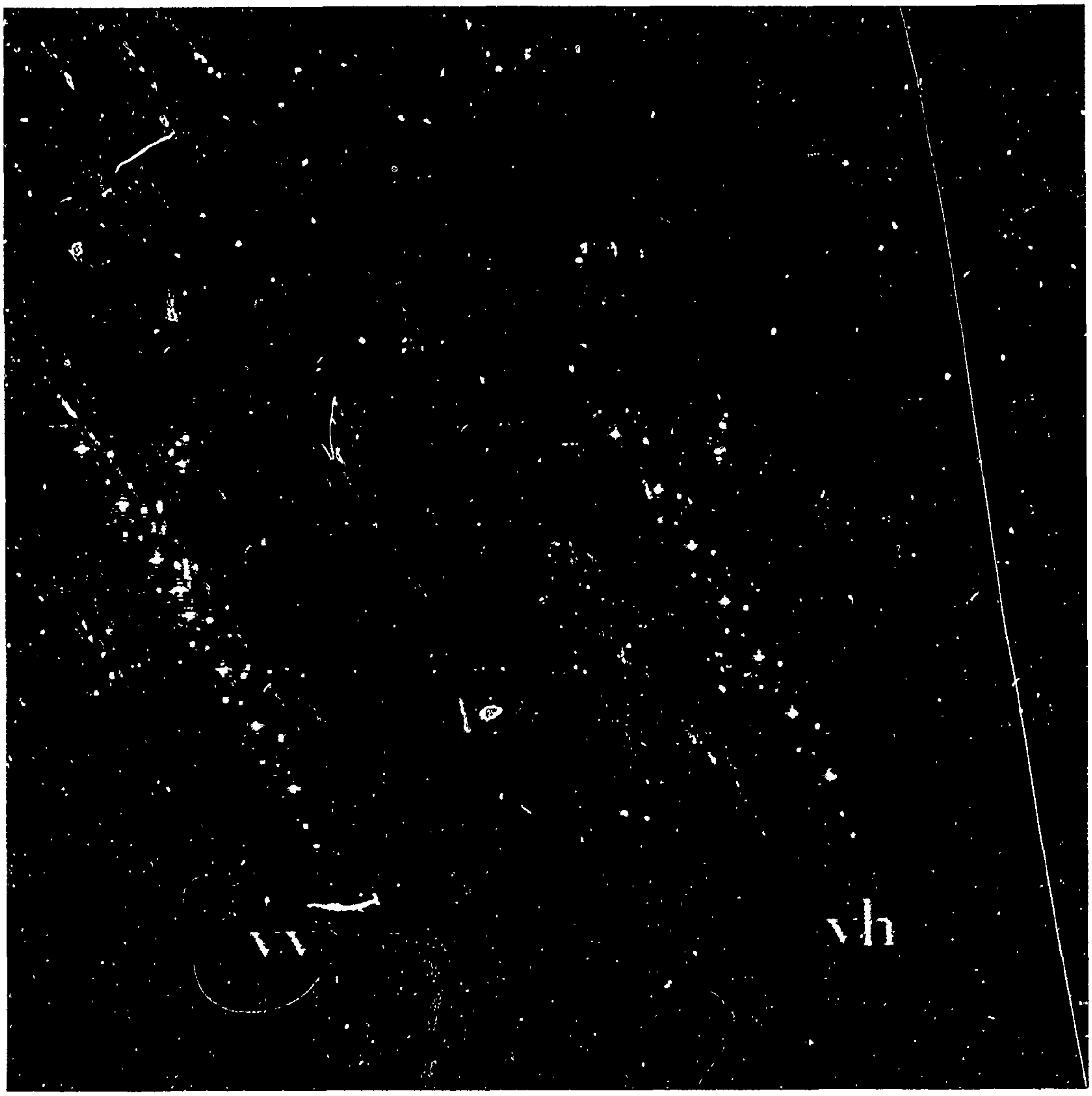


Figure 11. High-resolution SAR images of an M48 tank. In both images, cross range is plotted against range. On the left, the vertical/ vertical (vv) polarization components are shown; on the right, the vertical/ horizontal (vh). *(Images due to E. Davisson, BRL.)*

target in range and cross-range (along the flight path) but not in the remaining orthogonal direction. Thus the final SAR image orientation is similar to the optical rendering shown in the bottom left of Figure 10. A pair of computed SAR images for the M48 is shown in Figure 11. The labels vv and vh represent two combinations of transmit/ receive polarization (vertical/ horizontal) states. In addition, these calculations have been made in a high-resolution mode (about two-inch resolution) and are not constrained by practical frequency or coherence considerations of realizable radar systems. In each of these images, the radar signal is propagating from left to right. Range information is plotted along the abscissa and cross-range data along the ordinate.

The scattering of radar waves is determined by both target shape and material composition. Flat surfaces, particularly in combination, tend to reflect radar waves efficiently in preferred directions. A number of programs have been written to extract from target descriptions those surface shapes which are 1] flat only and 2] have dihedral (right-angle) elements. The information provided by these programs can be used as input to certain radar models as well as providing guidance in the minimization of signal return from US systems under design.

Finally, predicting the performance of high-frequency radars can be particularly challenging because of the geometric detail required as frequency increases. A tool which is finding increasing utility is illustrated in Figure 12. The objective is to characterize radar scattering at 94 Ghz to support smart munition as well as armored-fighting vehicle design. In the upper right portion of Figure 12, a US M109 self-propelled howitzer is shown from the left rear. This is an optical image of the actual vehicle. The middle right image is a plot derived from a 94 Ghz scanning radar (6-inch target resolution) set in a co-polarized mode. The cross-polarized mode is shown in the bottom right. To simulate this process, a target description of an M109 was built to a high-level of detail including high-resolution tracks and suspension system. This target was viewed from the same orientation as the actual optical image (upper right) and is shown in the upper-left corner. Using the lighting model described above, the target was given the properties of a purely specular (mirror-like) object. A single light source at the view position was used. The middle-left image shows the results. A glint image, highly suggestive of the right middle and lower images, is shown. The middle left image was low-pass filtered to achieve an even greater similarity with the field data shown on the right.

3.4 Summary of Signature Methods

This has been a brief review of some state-of-the-art techniques for predicting military signatures The general methods share an approach used for many other kinds of high-resolution calculations in item-level analyses. The procedure is based on the construction of computer files representing three-dimensional geometry and related material properties. These files are then linked to a particular application code based on the required signature, viewing angle, and other physical attributes.

4. OTHER ITEM-LEVEL ANALYSES

Of all item-level applications, the vulnerability and signature methods are the most heavily exploited by the weapons modeling community; nevertheless the possibilities and potential impact of this class of modeling goes far beyond these two disciplines In this section, a brief review will be made of other item-level applications which have been developed to date. Finally, some of the possibilities and issues connected with growing utilization of item-level modeling will be discussed.

4.1 Other Application Codes

- Weights & Moments-of-Inertia: As noted previously, when a target description is assembled, both the geometric shapes (internal as well as external) are fully defined. In addition, each geometric entity of the description is assigned a unique name to which specific material properties are related. For the task of weight estimation, the material density of each component or part is linked to the geometry. By firing mathematical rays in a tight grid and viewing groups of these rays, the composition of a target can be seen in high resolution. Figure 13 illustrates this process in which a 1" x 1" matrix of rays was fired through the front of a heavy tank target description. Groups of rays in horizontal sections were then extracted for individual viewing. Two are shown; the various gray levels (normally rendered in color) indicate the specific target materials (armor, ammunition, fuel, crew, air, etc.). If the material density information used for viewing is integrated over all rays in a given section, the weight of the target is derived for that particular one-inch thickness. If all sections are added, the weight of the entire system is estimated.

Such a process is important in many stages of weapons system evaluation. In all military systems, whether conceptual or fielded, air or ground, weight is a critical constraint.

By similar methods the Center-of-Mass and the Moments-of-Inertia (MoI) of a system can be estimated as well. The MoI are a measure of the torques required to change the rotational rate of a mechanical assembly.

The BRL-CAD tools have been used, for example, to estimate 1] the baseline weight of an M60, and then 2] the change in weight for various configurations of applique armor In addition, MoI calculations were performed with the applique layouts in order to estimate the required changes in the turret slewing hydraulics. These methods have also seen application in problems such as estimation of vehicle overturning moments due to nuclear (air) blast wave and a howitzer undergoing firing cycles.

- Neutron Transport: When a nuclear weapon is detonated, several threats to equipment and personnel exist. Among these is nuclear radiation. Using a computer code developed at Oak Ridge National Laboratory, the initial radiation output from a nuclear weapon can be track d from the point of detonation to a region within a military vehicle.

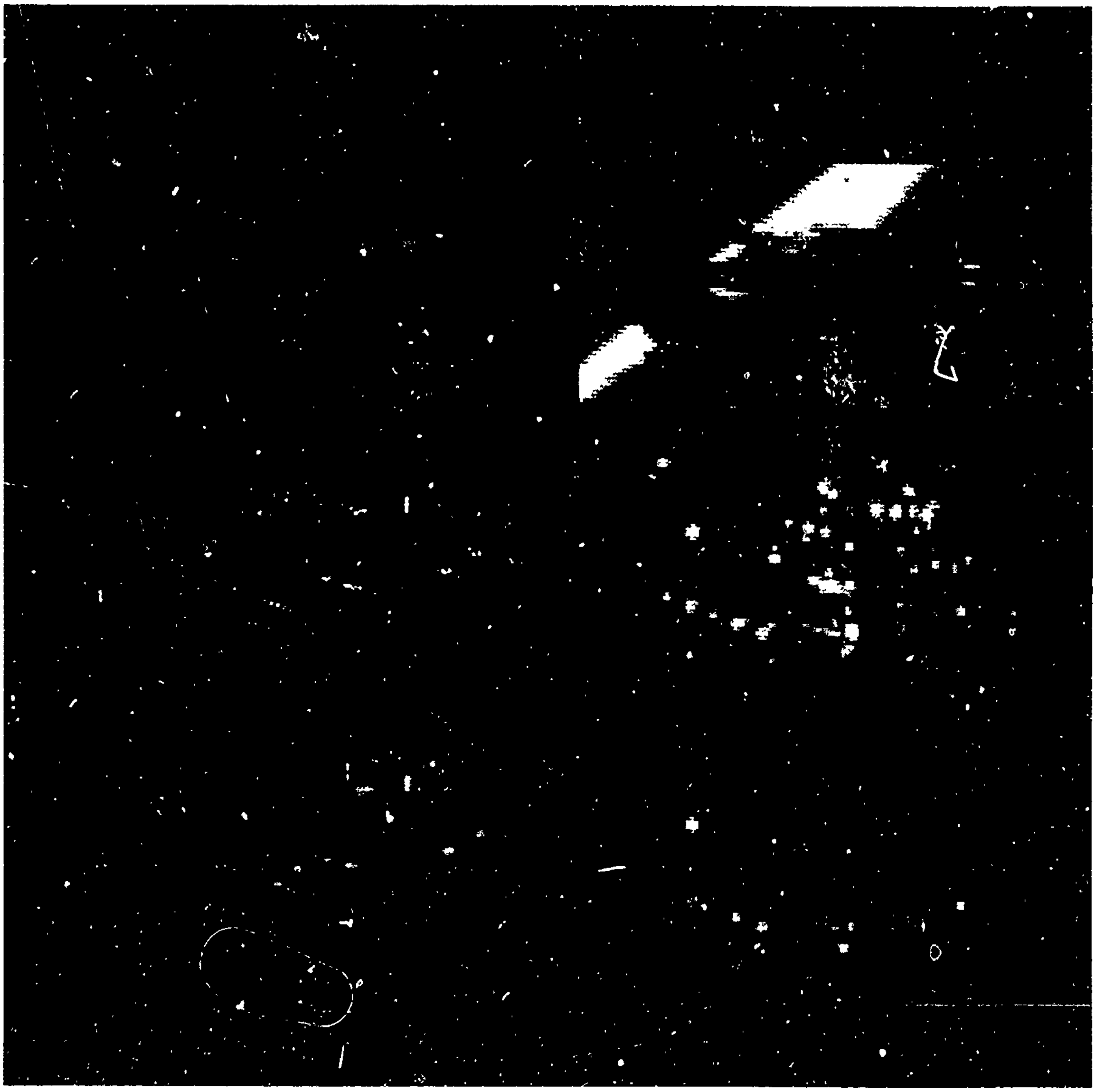


Figure 12. Comparison of 94 Ghz radar data with simulation for M109 self-propelled howitzer. Right-hand images are field-derived; left-hand are simulations. *(Experimental data due to H. Wallace, BRL, predictions due to T. Karr and E. Davisson, BRL.)*

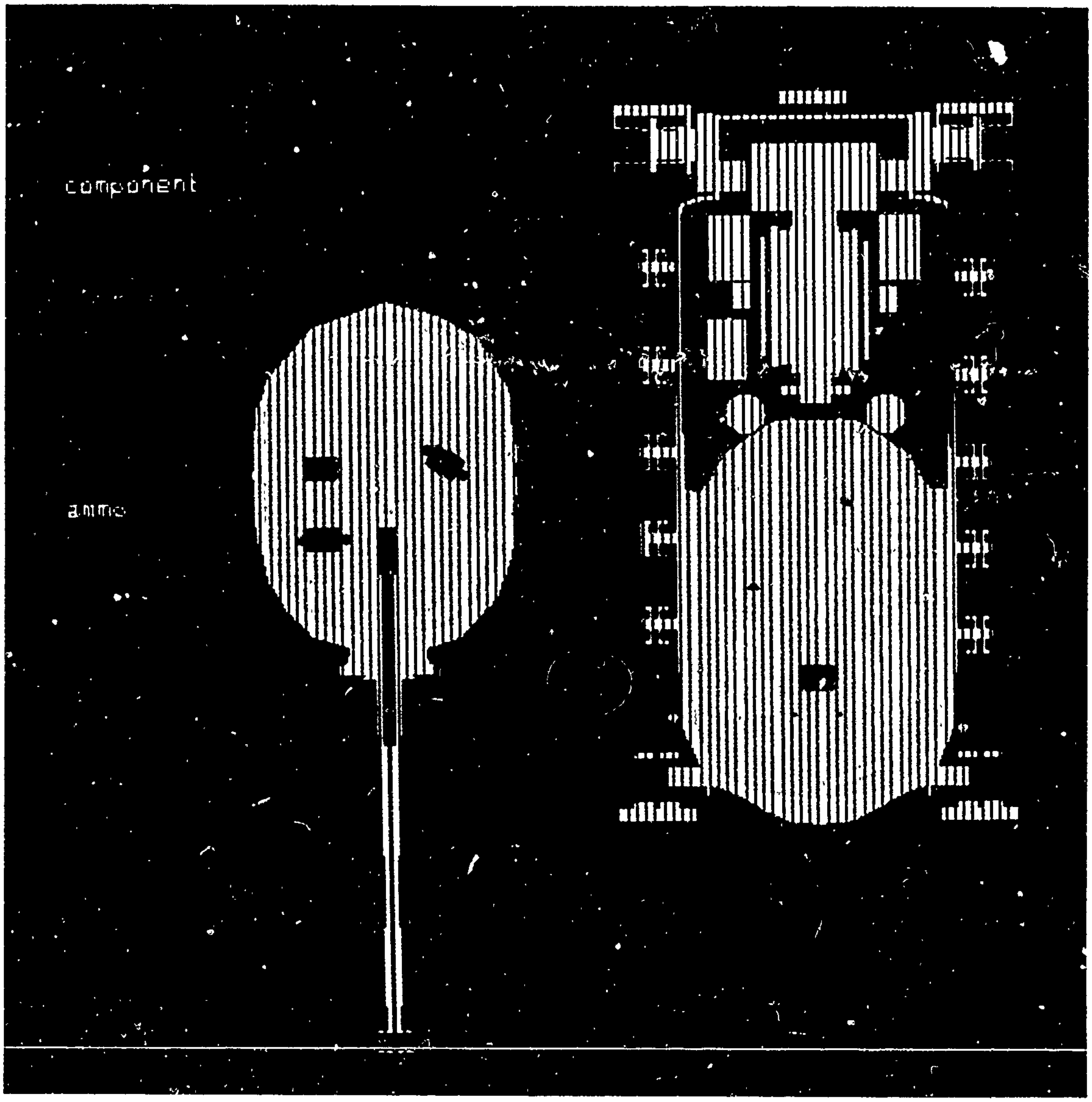


Figure 13. High density shotline sections through a tank target description; various line shadings denote different material densities. *(Calculations by R. Suckling, BRL.)*

A number of years ago this code was used to estimate the neutron dosage just below the driver's hatch in a concept vehicle. Called the Tank Test Bed, one particular configuration is illustrated in the upper half of Figure 14. In this study, the total radiation dose reaching the driver's head was calculated while monitoring the specific exterior portions of the vehicle through which the radiation leaked. In the lower half of Figure 14 the image shading has been adjusted according to the magnitude of neutron flux. Higher neutron flux surfaces are shown in lighter shades.

- Structural/Acoustic Analysis: Structural integrity is an important issue in the design, analysis and testing of military items. It is clearly a central issue for both fixed and rotary-wing aircraft; in the past it has not been an issue for heavy tanks, but now has taken on increasing importance with lighter fighting vehicles, particularly as the use of explosive applique armor has been considered.

A baseline calculation is often employed to yield the so-called "static case" in which a steady force is applied to a portion of a vehicle. Such a pilot study was performed using a chassis design for a Mobile Protected Gun System (MPGS). The BRL-CAD geometry assembled for vulnerability analysis was translated into the CAD format of a commercial finite-element preprocessor (PATRAN ™). Inside this modeler the chassis was subdivided into discrete elements and then passed to a finite-element code (ADINA ™) where a steady force corresponding to the turret weight was applied to the region of the turret ring. Figure 15 below shows the von Mises stresses calculated over the chassis. The results reveal a conservative design, far below the levels at which plastic deformation begins.

The same finite-element medium can be used for other classes of calculations. One study performed involved calculating the natural harmonic frequencies of this chassis design together with the amplitudes of oscillation. Such results can be important in reducing harmonic resonances which can affect vehicle mobility; they relate as well to the acoustic signature of the vehicle.

- High-Energy Laser. In the 15 years prior to 1984, many high-energy laser experiments were carried out, these tests established an effects data base for lasers of various wavelengths (primarily 10.6 and 3.8 microns) and wave shapes (pulsed and continuous) During the same time vulnerability tests were conducted to establish component-damage thresholds, particularly for those utilized in optical systems, missiles and aircraft. The information gathered in this testing has been used to assemble a laser-damage effects model BRL-CAD target descriptions, giving the three-dimensional geometry and material definitions, serve as part of the input This information is combined with illumination dwell times and damage thresholds to compute likelihood of component degradation/ target destruction.

- High-Powered Microwave (HPM). HPM weaponry is currently in the exploratory research stage. The coupling of microwave energy to the components of a target is an extremely complicated, non-separable problem. Linkage can occur *via* "front-door" avenues, such as through antennae which are designed to collect low power microwave signals, or through "back-door" channels, such as cracks and seams in the outer vehicle skin These potential channels and their unavoidable interplay result in the need to analyze systems as a whole in order to achieve reliable target kill assessments. A goal for HPM is development of a computer-based methodology which uses the standard BRL-CAD target models (perhaps with some augmentation) in the assessment of target vulnerability. The development of a computer model has been contracted for and the first-stage deliverables are under review.

- X-Ray Simulation. Recently an extension was made to the BRL-CAD environment to simulate the behavior of X-rays in materials. The radiation source can be placed at an arbitrary point in space. A series of rays are then extended through the object for which the simulation is to be performed. The material attributes assigned to the regions of the object can be related to actual X-ray absorption. Thus the energies emerging at the far side of an object can be calculated and then transformed according to the efficiencies typical of film detection. Images have been derived for a number of objects including portions of heavy tanks. Such techniques may be of aid in the interpretation of experimental X-rays normally taken in armor penetration studies or other noninvasive tests.

The techniques described here and in the previous sections represent current methods of high-resolution item-level modeling. By inference, many other kinds of applications can be supported, limited only by the imagination of the analyst.

4.2 Planned BRL-CAD Upgrades

The capabilities of the current set of tools derive mainly from the distinct requirements of the vulnerability and signature communities. However it is recognized that there are specific extensions which would bring the utility of these tools to other users with their own distinct requirements.

- Blueprints: For a significant number of weapons analysts today, the world of CAD means aiding the process of blueprint generation. Although the BRL-CAD tools can generate elegant optical images as well as the simpler scaled "wire-frame" drawings, such output falls far short of the requirements for dimensioning, tolerancing, and other standard fare of the industrial-design world Two approaches to gaining this capability are being examined. One involves generating blueprints directly from a BRL-CAD data base *via* a set of stand-alone software. The other approach involves creating a mapping code capable of transforming target descriptions generated with BRL-CAD into a format used by a second modeling system already capable of blueprint generation.

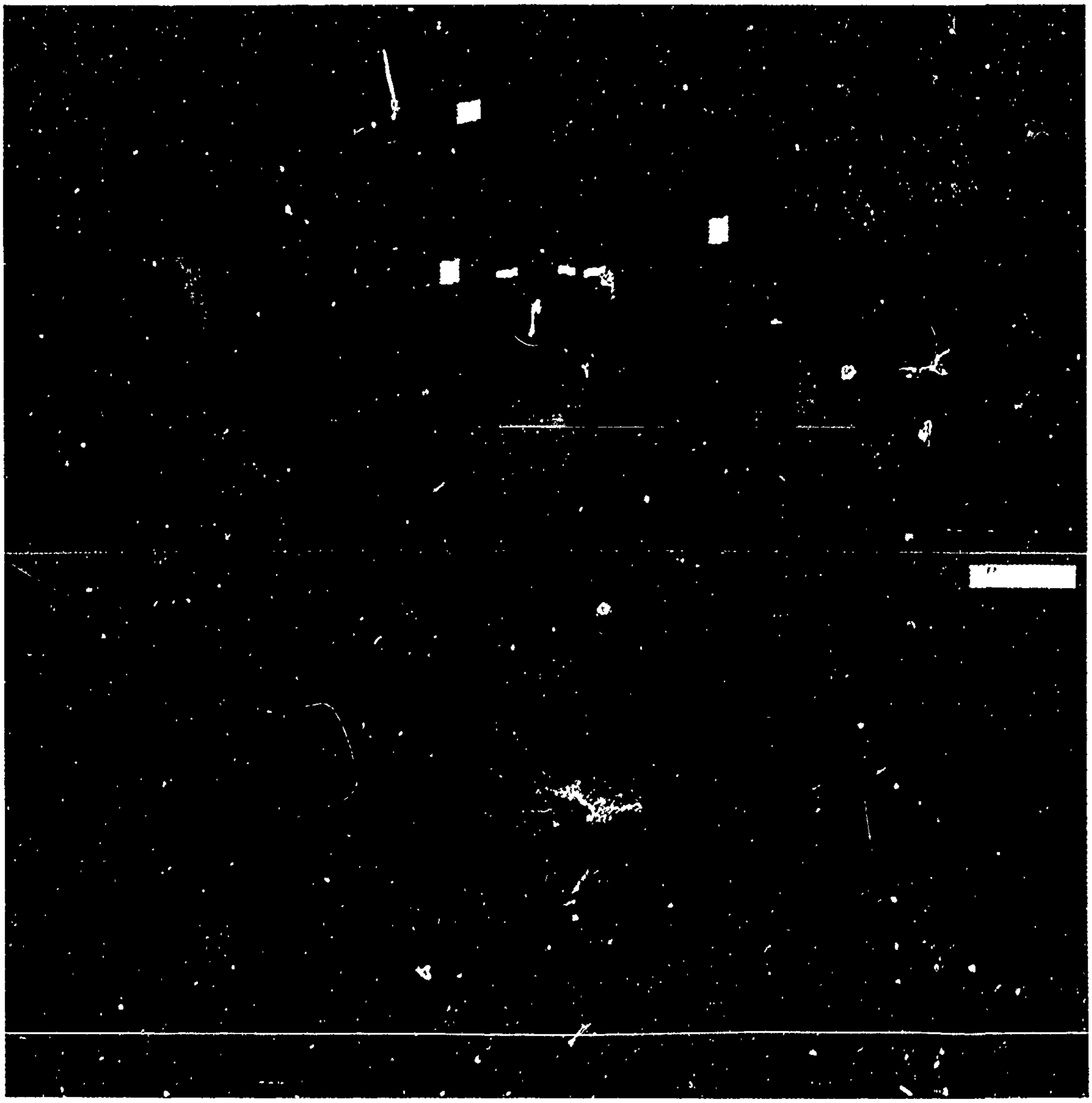


Figure 14. Neutron transport calculations for a concept heavy tank. *(Prediction due to J. Kinch, BRL.)*

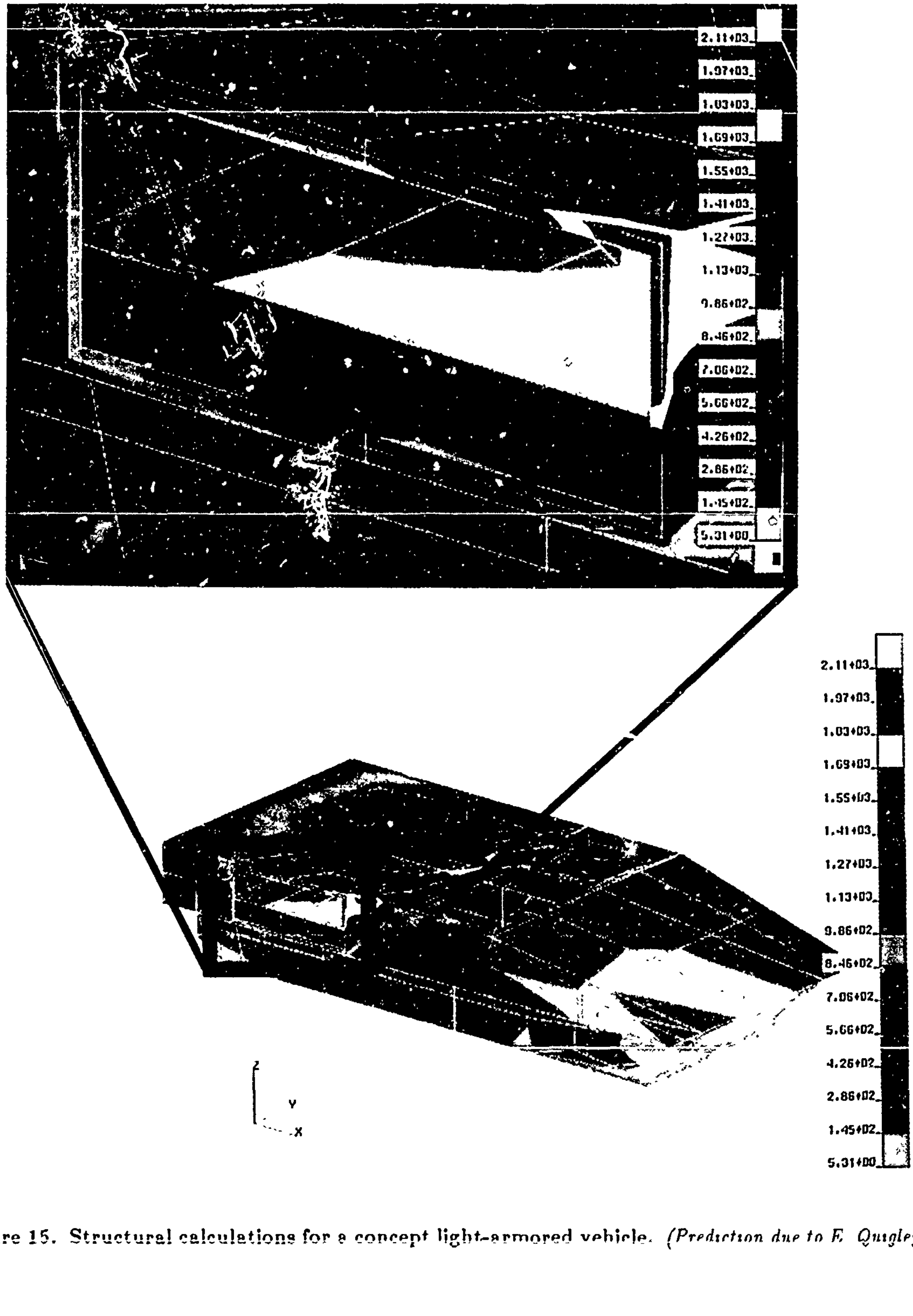


Figure 15. Structural calculations for a concept light-armored vehicle. *(Prediction due to E. Quigley, BRL.)*

- 3-D Mesh Generation. The origins of the current set of BRL-CAD software arose 20 years ago in order to support vulnerability and neutron transport analyses. The way in which the early analysts chose to link the target descriptions with the applications codes was through ray casting (or ray tracing). This method fits conveniently the notion of bullet and neutron trajectories, and indeed the majority of codes illustrated in this article use ray casting as the means of connection.

There exists, however, an important body of applications codes which, rather than depending on ray tracing, require geometry described in terms of a regular collection of facets, or flat approximations to the actual geometric surfaces. The BRL has initiated a project to develop software capable of transforming the standard form of target descriptions into one composed entirely of such facets; the size or courseness of such facets would be set by the user.

The success of this project could open important new avenues of analysis. For example, some predictive thermal codes (such as the PRISM model developed at TACOM) require facets as the basic building block for analysis. Certain radar codes (such as one in use at Northrop) require a target model composed of facets so that numerical integration methods can be applied directly to the geometry. Also many of today's most powerful interactive computer workstations have on-board hardware capable of performing real-time image generation for geometry supplied in a facet format.

4.3 Future Issues

Currently the AMC has a renewed interest in CAD. A charter for an AMC Functional Coordinating Group for Computer Aided Design-Engineering (CAD-E) was approved on 24 February 1989 The CAD-E Group is directed to make a strategic assessment of AMC CAD-E efforts, evaluate the feasibility of a standard CAD-E system and determine how such a system would be maintained.

An issue which is always problematic involves the extent to which standards should be imposed on a particular community of users. Without some standards, interchange of data may become difficult or impossible

The plethora of ways in which geometry can be represented is in fact the reason solid geometric data generated by one commercial modeling system generally cannot be used by another vendor's system Sometimes the basic geometric constructs used in one system simply cannot be exactly handed over to another due to mathematical constraints. Another typical incompatibility arises because most vendors choose to keep the nature and format of their data base inaccessible to the user. This is a commercial strategy referred to by some as "vendor lock in". The government-supported Initial Graphics Exchange Specification (IGES) has been moderately successful at defining standards for sharing wire-frame (or drafting-level) geometry but is unlikely to provide a common meta-language specification for the solid modeling world The approach taken in the BRL-CAD environment has been to modularize those parts of the software in which the mathematical definitions of 3-D shapes play a role. Tools have been developed so that as new mathematical forms are required, they can be added easily at these key sections of code. All other parts of the environment, including interfaces to applications codes, remain unchanged.

The first foray into using BRL-CAD as an Army standard begins now with the Heavy Forces Modernization (HFM) thrust. The objective of HFM is provide the Army with the optimum ground-vehicle fleet in the year 2004; nearly 30 vehicle types are included. All vendors will be required by contract to submit geometric and material descriptions of vehicle designs in the BRL-CAD format and to provide updates at six-month intervals.

On the other hand, with too many standards, technical innovation can be stifled. Such a situation could arise in a future weapons procurement if both a solid-modeling requirement and the new DoD Computer-Aided Acquisition and Logistics Support (CALS) system are applied. CALS is a laudable interservice effort to provide standards for computer-aided design drawings, text formatting, graphics and pictures. However since solid geometric data is a complete form of specification as opposed to blueprint-level specification, the former is not derivable from the latter. If the latter were defined to be the primary deliverable under a government contract, it might well preclude the use of the more advanced technology. These and related issues will provide interesting challenges as the electronic age advances.

In a time of shrinking resources, the maintenance of BRL-CAD software and related data bases is receiving increasing attention. At least three aspects are involved:

[1] The CAD package itself has been distributed to over 450 computer sites. Code and documentation must be written and distributed, bug-fixes performed, and extensions made as new capabilities are sought.

[2] Various inhouse applications codes (vulnerability, signature, etc.) must be maintained, extended, and distributed within a growing community of users. Also codes developed by outside users need to be brought in, examined, and sometimes installed for inhouse production use.

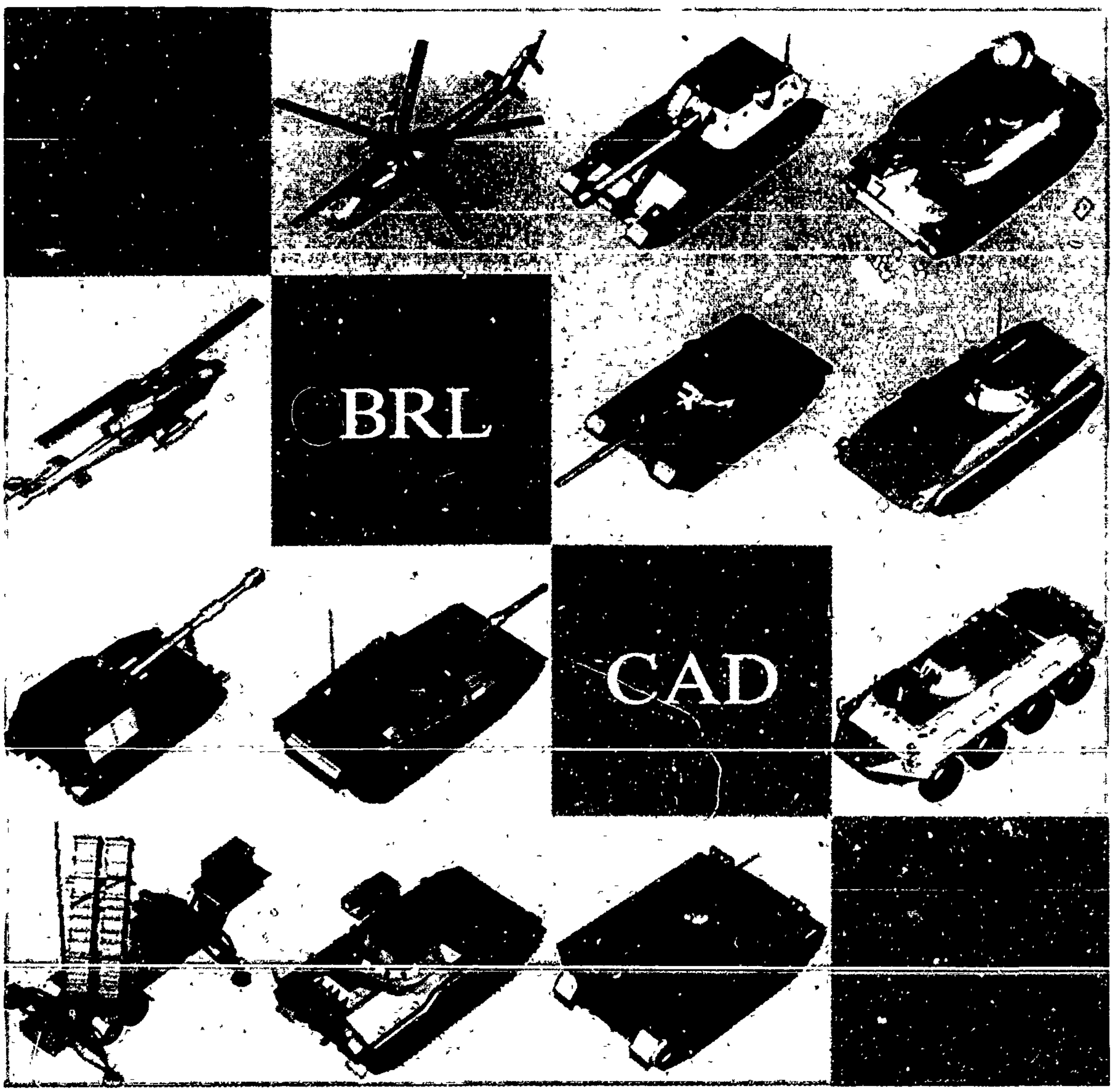
[3] Among the community of target-description providers [BRL, Denver Research Institute (see Section **1.3**), and other contractors] there now exist hundreds of military target descriptions, domestic and foreign, in a shareable format. Mechanisms must be found and implemented for storing, sharing and upgrading these valuable assets.

4.4 Summary of Other Application Codes

In this review, many modern computer-based methods have been described in support of high-resolution item-level weapons modeling. Without doubt these methods will enjoy increasing use both throughout government and industry. This exploitation is possible because of a number of factors including the establishment of rigorous algorithms, the uniform support provided by modern computer software environments, and the power and low cost of today's computer hardware

The development of these tools is due to the efforts of many scientists and analysts, it is significant that a major portion of these modern analytic methods owe their existence to Army-sponsored and staffed research.

Dr. Paul H. Deitz is Chief of the Vulnerability Methodology Branch, Vulnerability/Lethality Division, of the USA Ballistic Research Laboratory. He holds a bachelor's degree in physics from Gettysburg College and masters and Ph.D. degrees in electrical engineering from the University of Washington.



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